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# AN ANALYSIS OF THE FORMATION OF STACK SOLIDS FROM THE COMBUSTION OF HEAVY FUEL OILS

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# AN ANALYSIS OF THE FORMATION OF STACK SOLIDS FROM THE COMBUSTION OF HEAVY FUEL OILS

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Submitted in Partial Fulfillment
of the Requirements for the Degree of
MASTER OF SCIENCE
in
NAVAL CONSTRUCTION AND ENGINEERING
from the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
1948

Thesis
S5

Cambridge, Massachusetts,
January 16, 1948.

Professor J. S. Newell,
Secretary of the Faculty,
Massachusetts Institute of Technology,
Cambridge, Massachusetts.

Dear Sir:

In accordance with the requirements for the Degree of Master of Science in Naval Construction and Engineering, we submit herewith a thesis entitled "An Analysis of the Formation of Stack Solids from the Combustion of Heavy Fuel Oils".

Respectfully,

# ACKNOWLEDGMENT

The authors wish to express their appreciation to Professor H. C. Hottel for his help and advice, and for the suggestion which originally inspired this investigation. The cooperation and skill of the employees of the Boston Naval Shipyard made possible the construction of the equipment.

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# SUMMARY

The process of combustion of fuel oil has been studied by other investigators. The work performed has covered the combustion history of an individual fuel drop, combustion of asphaltine residues, and the formation of stack solids using a large furnace such as a locomotive boiler. The results of these investigations have shown the effects of operating variables on the stack solid problem; however, a complete analysis has not been made.

A rigorous treatment of the combustion process as it occurs in a furnace has to deal with a cloud of particles of non-uniform size, burning away in an atmosphere of changing physical and chemical nature. Furthermore, the studies conducted so far have never used a laboratory furnace, but have used furnaces which required considerable expense and time to operate.

The purpose of the current investigation was to design a laboratory furnace to burn a finite quantity of oil under conditions that approximate boiler furnaces, i.e. temperature levels, firing rate per unit of volume, etc. The design was to be such that the effect of each control variable on the formation of stack solids could be investigated independently. The factors which affect the completeness of combustion are the nature of the fuel oil, particle size, temperature, furnace atmosphere, the relative velocity between the particle and the furnace gas, and the combustion time.

Considerable time was spent in the desigh, construction and assembly of the equipment to fulfill the various requirements. The equipment developed incorporated the following features: (1) A long, small cross-section furnace burned down draft. This eliminates, as far as possible, variations in path length and effect of relative velocity. (2) A method of quenching the products so that the approximate combustion time is determined by flow rates in the furnace proper. (3) A method of controlling the air rate, firing rate and particle size. (4) A method of collection of the stack solids formed.

The scope of the experimental procedure was limited by the time required to get the equipment in operating condition. It consisted of combustion of fuel oil at the rate of approximately 170,000 BTU/cu.ft. of furnace volume per hour, and collection of the stack solids formed. The quantity of stack solids formed from combustion of two fuels, Navy Special and a commercial Bunker "C", was determined for the same combustion conditions. The effect of excess air was determined by combustion of Navy Special fuel oil under different conditions.

The results show that the nature of the oil is an important factor in determining the quantity of solids formed. The unburned carbon content of the residue increases as the weight percent of stack solids increases.

The effect of excess air is not a simple function. The "effect of the excess air" is without meaning unless it is

specified whether the variation is accomplished by changing the fuel rate or the air rate.

The appearance of the residues substantiates the combustion theory proposed by Chang (6). The mechanism is quite complex, as indicated by the different forms of the residues.

The performance of the equipment was good; it was possible to fulfill the requirements of a suitable laboratory furnace. The results obtained were consistent with those of other investigators.

A new method of presentation of the data is suggested. On this basis there is an optimum firing rate and air rate for a given furnace and a given fuel. There exists also an optimum condition for either of the above parameters when the other is fixed.

## INTRODUCTION

It was formerly believed that the combustion of fuel oil took place entirely in the vapor phase. Flame luminosity and soot formation were attributed to the carbon particles formed by the cracking of the hydrocarbon vapors. More recently, it has been found that the solid residue from the incomplete combustion of heavy fuel oil is composed of two types. One type is formed by cracking of the hydrocarbons in the vapor phase, and is a soft fluffy soot. The second type, referred to as stack solids, appears as cenospheres*, or compact spherical coke particles.

The work of Chang (6) and Gerald (7) on combustion of single droplets of heavy fuel oil proposed the theory that combustion takes place in three stages: preheating to the boiling point, vaporization and burning of the hydrocarbon vapors, and heterogeneous combustion of the coke residue. Soot is formed in the late stages of evaporation when the unstable hydrocarbon vapors are evolved. It is formed at the core of the vapor where cracking conditions are such that the carbon particles agglomerate into large particles before oxygen can penetrate by diffusion. The agglomerated carbon particles then have to burn by the slow process of heterogeneous combustion. It is also toward the end of the vaporization stage that the form of the stack solids is determined.

* Cenospheres - hollow spheres of well-defined structure.

During this period, there is internal vaporization in the oil particle and the ease with which this vapor is driven off determines whether the solid left behind is a swollen cenosphere or a shrunken compact coke particle with a large number of small pores on the surface. For the particular heavy fuel oil studied by Chang, cenospheres were obtained at 800° C and compact coke particles at 900 to 1100° C.

The combustion process as it occurs in a furnace has to deal with a cloud of particles of different sizes burning in an atmosphere of changing physical and chemical conditions. The factors affecting the completeness of combustion of fuel oil particles in a furnace are: (1) the nature of the fuel, (2) particle size, (3) temperature, (4) furnace atmosphere, (5) relative velocity between the particle and the furnace gas, and (6) the time in the furnace.

## THE EQUIPMENT

An essential part of the work to investigate the problem was to design equipment that could be used to study the effect of the controllable variables independently. Some of these variables may be studied with a comparatively simple installation. These are the nature of the fuel, particle size, furnace atmosphere and combustion time. The design was made to study these variables.

The design is based on straightforward calculations. The arrangement of the equipment is shown in Figures I and II; it consists of the following components:

Furnace - The size of the furnace was selected for a combustion rate of 170,000 BTU/ cu. ft. of furnace volume/hour at a fuel rate of approximately two (2) gallons per hour. A long chamber of small cross-section fired down-draft was used to minimize possible variation in path length of the fuel particles. No provision is made for temperature control of the furnace; the temperature level depends on the firing rate and the amount of excess air used. The furnace casing is fitted with small openings at equal intervals of length to permit observations of combustion or temperature measurements. The top section is fitted with connections to permit use of city gas in warming up. The furnace volume may be decreased by removing the lowest section of the furnace. A double purpose refractory and insulating brick is used to simplify the construction. The details of construction of the furnace are shown in Figures III, IV and V.

Quenching Unit - The purpose of this unit is to cool the products of combustion leaving the furnace to a temperature low enough to stop combustion. This requires transfer of extremely large quantities of heat in a minimum length with an arrangement such that the collection of solids is a minimum. A single row of thin-walled copper tubes was used and the heat transfer surface was obtained by using flattened 2" diameter tubes with the narrow dimension perpendicular to the direction of gas flow. The unit is quite interesting since the products were cooled from temperatures in excess of 2100°F to 1100°F. The furnace could be brought up to operat-

ing temperature within fifteen minutes with only minor leakage caused by opening of the flanges. The unit required considerable time and effort in construction because of necessity for experimentally determining the spacing of the tube support plates to prevent excessive deflections under operating pressure. The details of construction are shown in Figures VI, VII and VIII.

*Fuel Supply* - A gravity feed tank was used because of its simplicity. The capacity of the tank was one gallon and the tank was fitted internally with a 1000-watt Calrod heater, hand stirrer, and thermometer. The fuel orifice was calibrated for a fuel viscosity of 150 SSU. City gas was used for warming up before starting an oil run. The supply is controlled by a single throttle valve and no provisions were made for metering the gas. The position of the gas jets in the furnace is shown in Figure IV, Section A-A.

*Fuel Atomizer* - Air atomization was used; the method employed was studied by Nukiyama and Tanasawa (10). This method has certain desirable features: (1) wall impingement is minimized, (2) at high air-fuel ratios the particle diameter depends on the relative velocity of the fuel and air streams only, and (3) it permits the study of the effect of air-fuel ratios, particle size, and firing rate independently. The assembly of the atomizer is shown in Figure IX. Further dedetails of the theory are given in the Supplementary Introduction.

Separating Unit - The separator is of conventional cyclone separator design. The efficiency of the unit was not determined, but it was designed for a minimum inlet velocity of 20 ft./second to insure adequate collection efficiency. The relative dimensions were based on experience and were recommended by private communication. The separator is shown in Figures X and XI.

Control and Measuring Instruments -

1. Air - An ASME sharp-edged orifice with vena-contracta pressure taps was used to meter the air. A by-pass valve was used to control the quantity of air. The blower was driven by a 1.2 HP motor and had a capacity of 71 cu.ft./min. at 18" of water.

2. Temperatures - Fuel and air temperatures were measured by thermometers. Chromel-alumel thermocouples were used to measure the furnace and the exhaust gas temperature. The furnace thermocouples were installed as shown in Figure V with alundum protection tubes. The calibration of the thermocouples is unimportant since the primary purpose is the measurement of relative temperatures and to determine when the furnace has reached an equilibrium temperature. The exhaust gas thermocouple was fitted with a single cylindrical shield. The location of all thermocouples is shown in Figures I and II.

3. Gas Analysis Equipment - A Fisher unitized precision gas analysis unit was used.

Figure I
Arrangement of Equipment

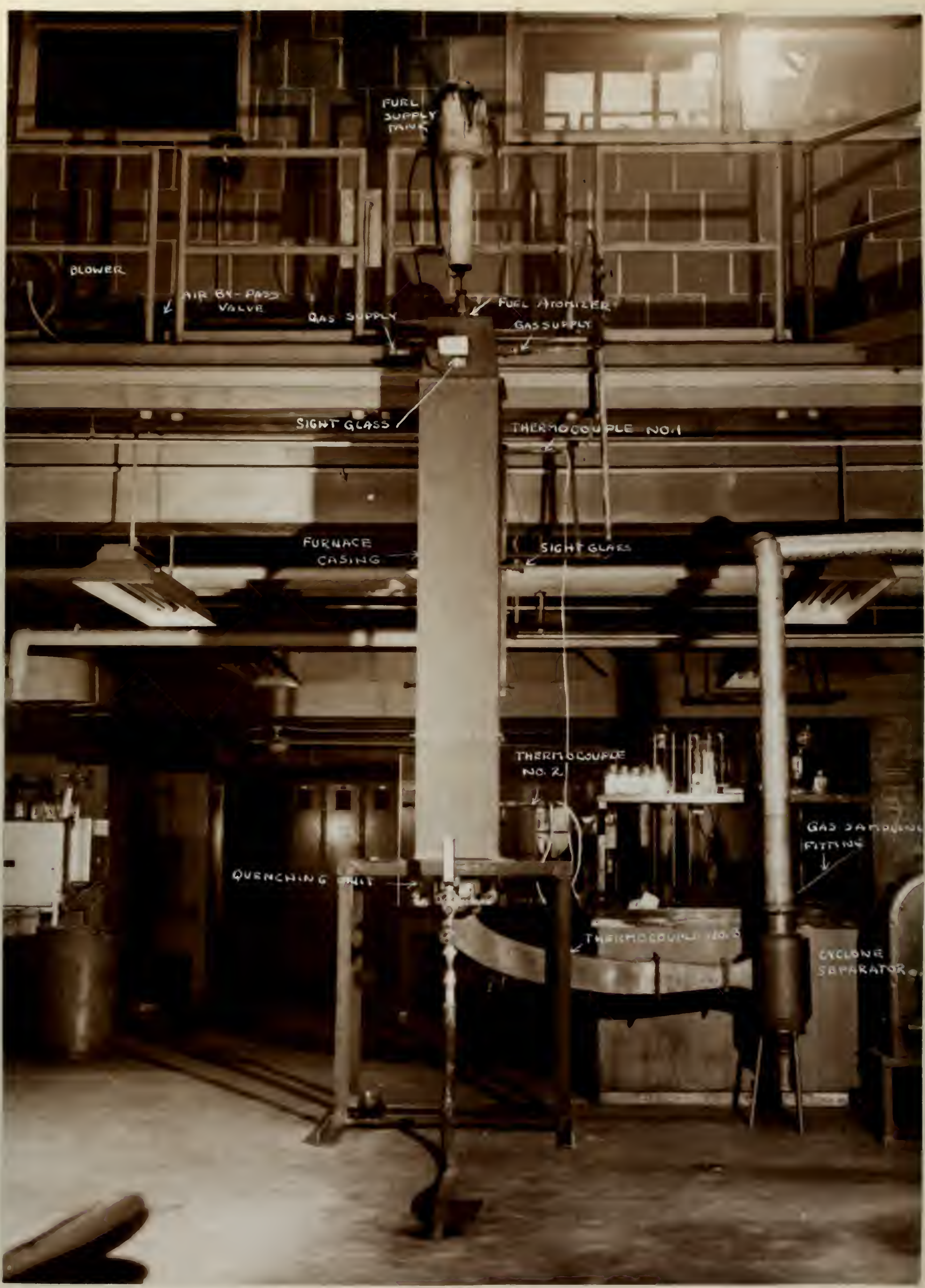


Figure II

Arrangement of Equipment

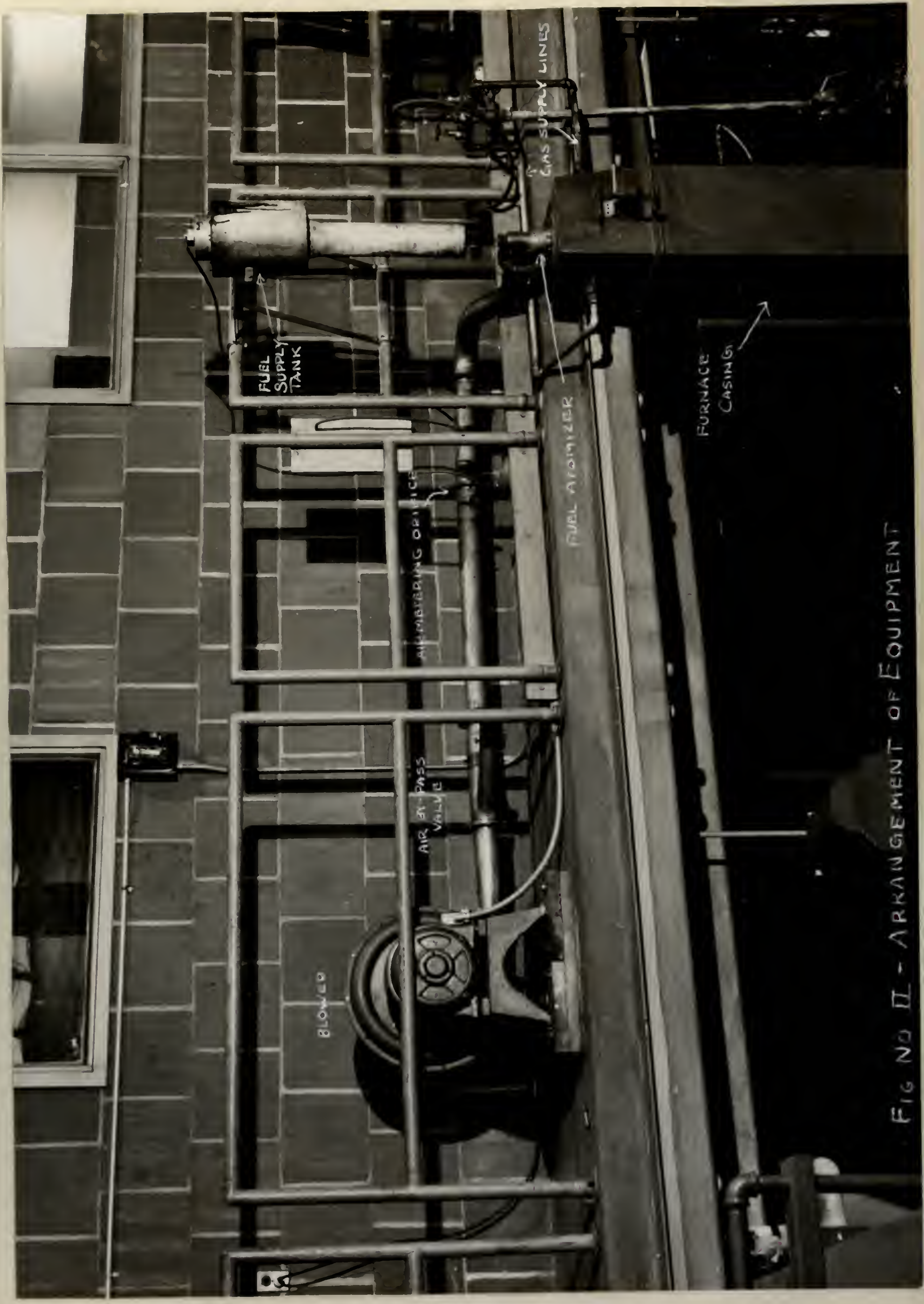
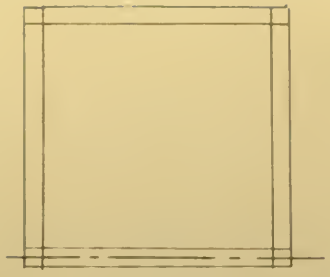
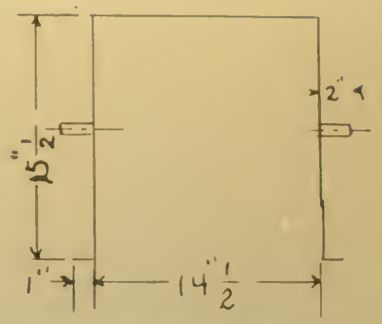


FIG NO II - ARRANGEMENT OF EQUIPMENT

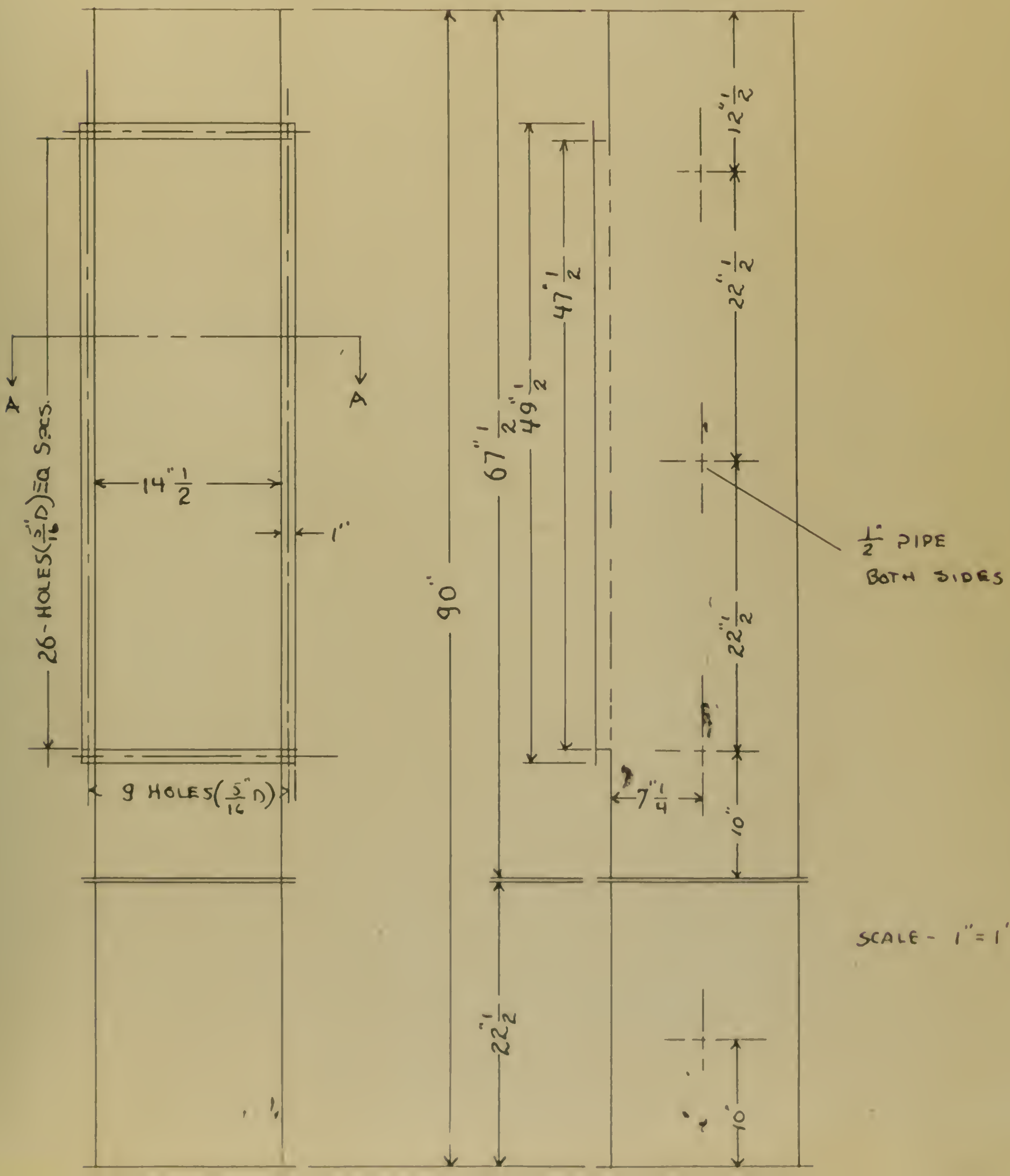
# FIG III



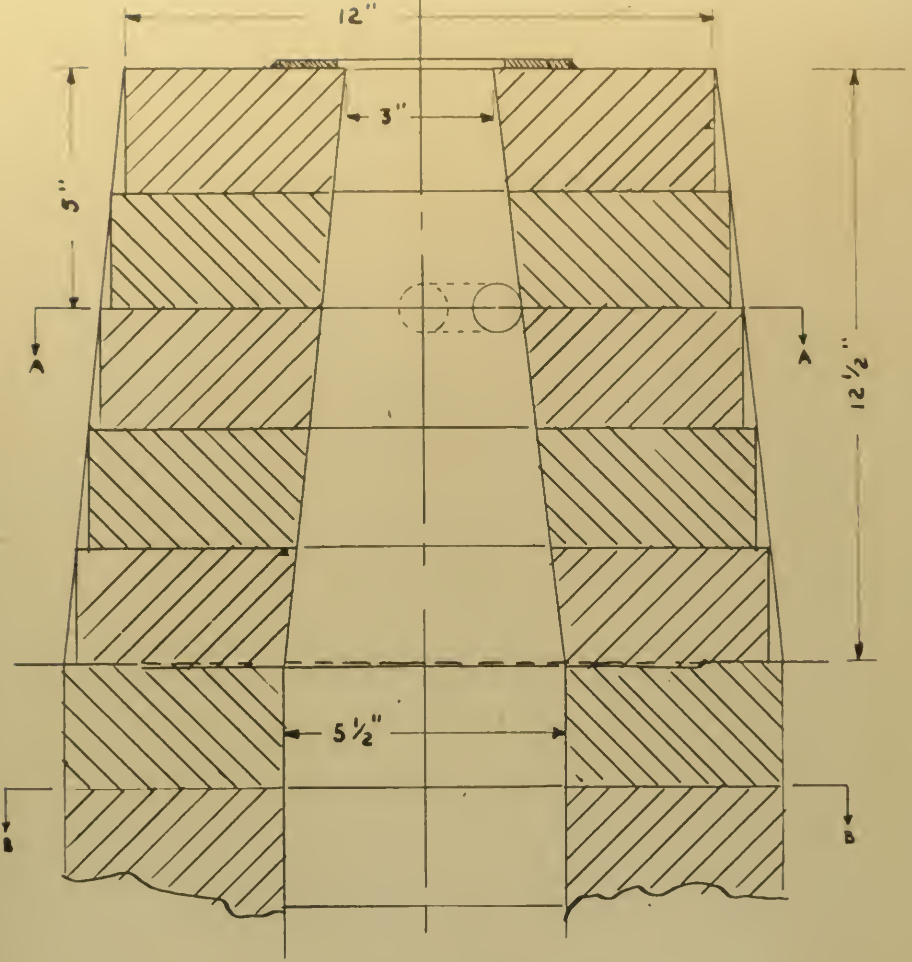


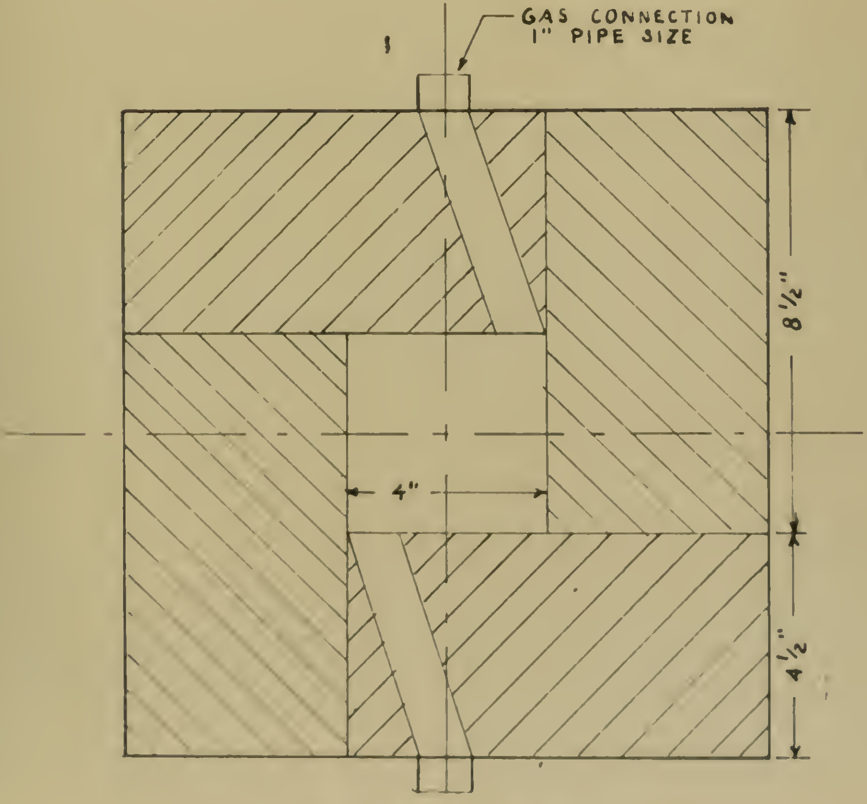
A-A

FURNACE CASING



SCALE - 1"=1'





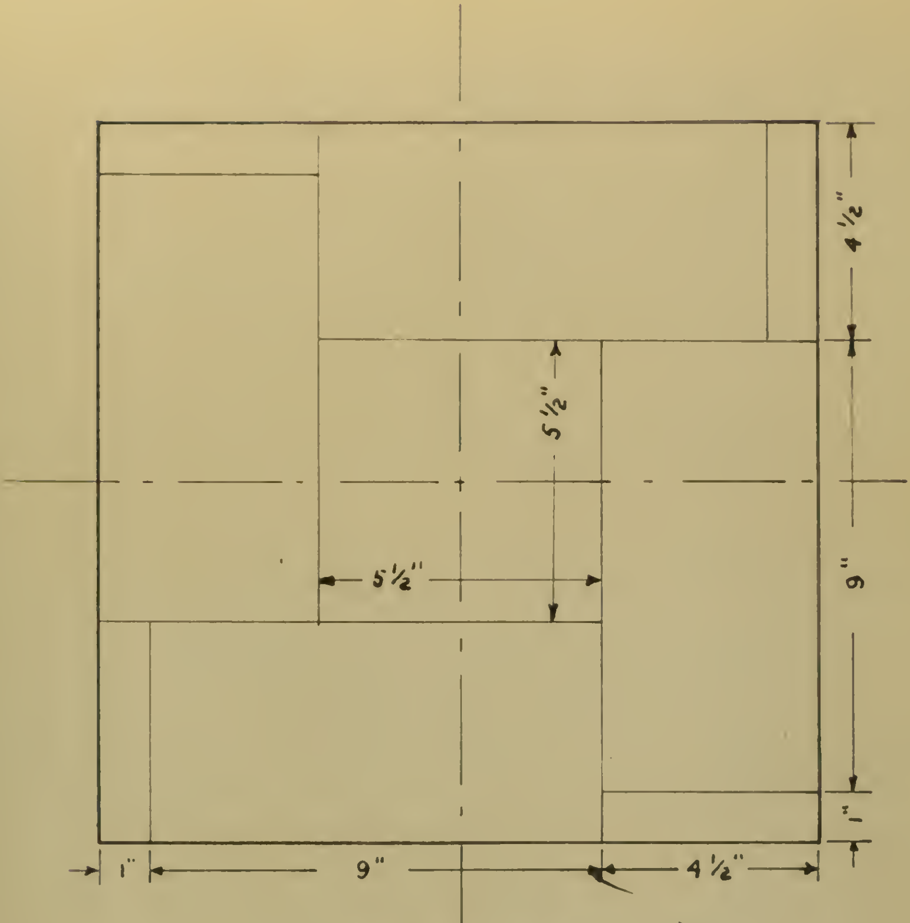
SECTION A-A

FIG IV

FURNACE CROSS-SECTIONS

FIG V

FURNACE CROSS-SECTION



SECTION B-B

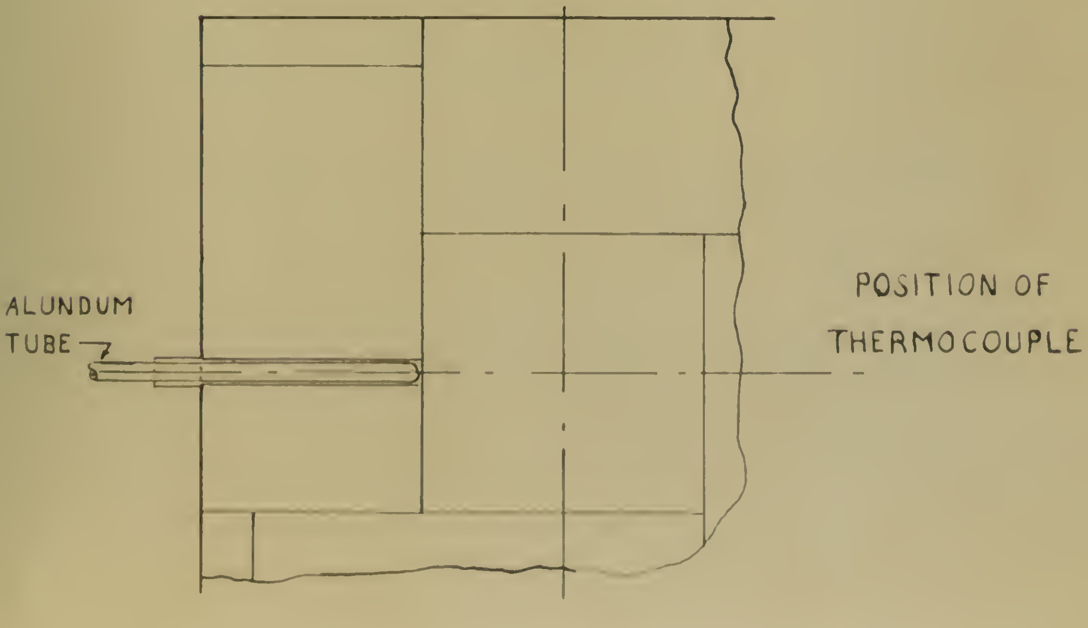
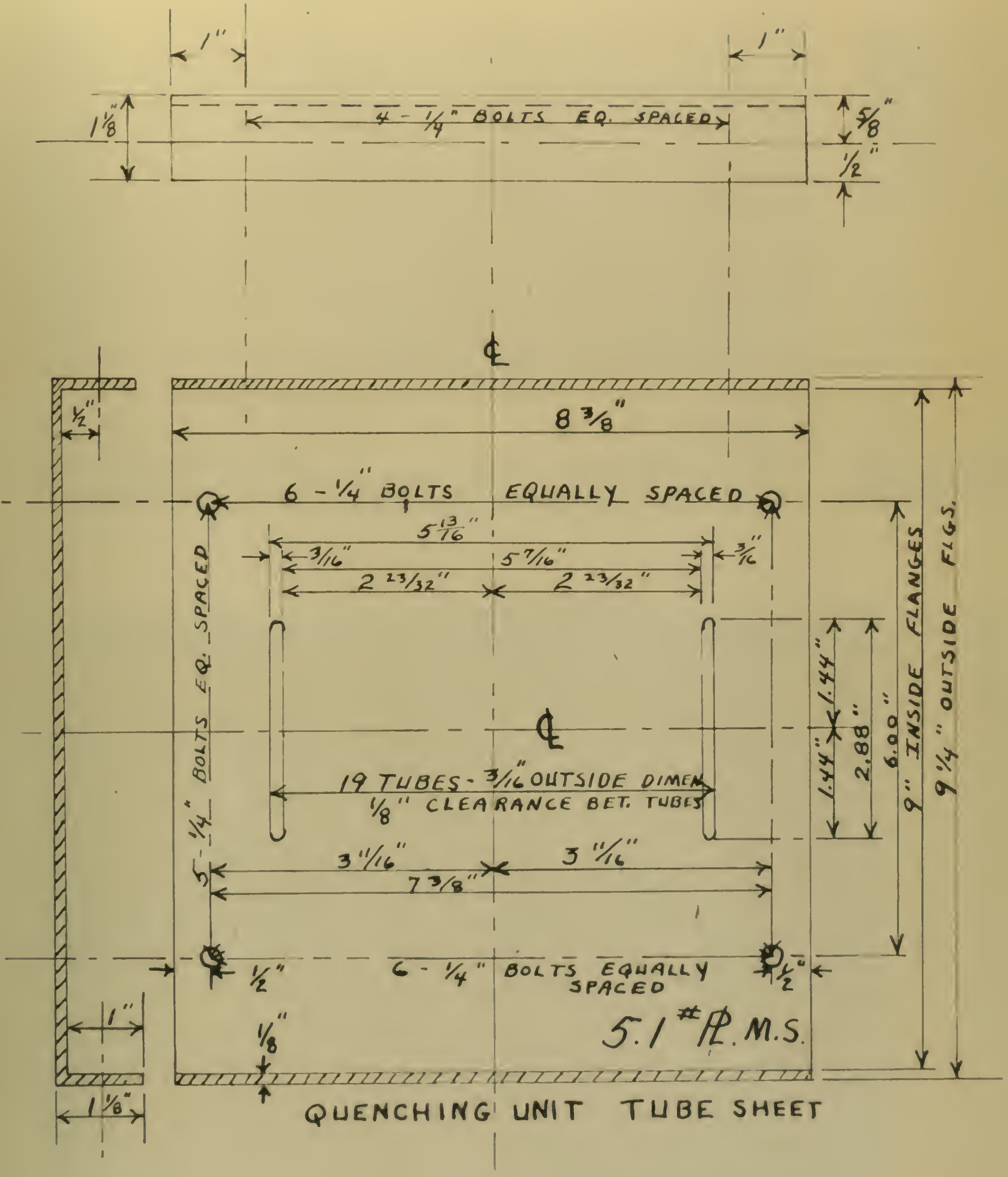
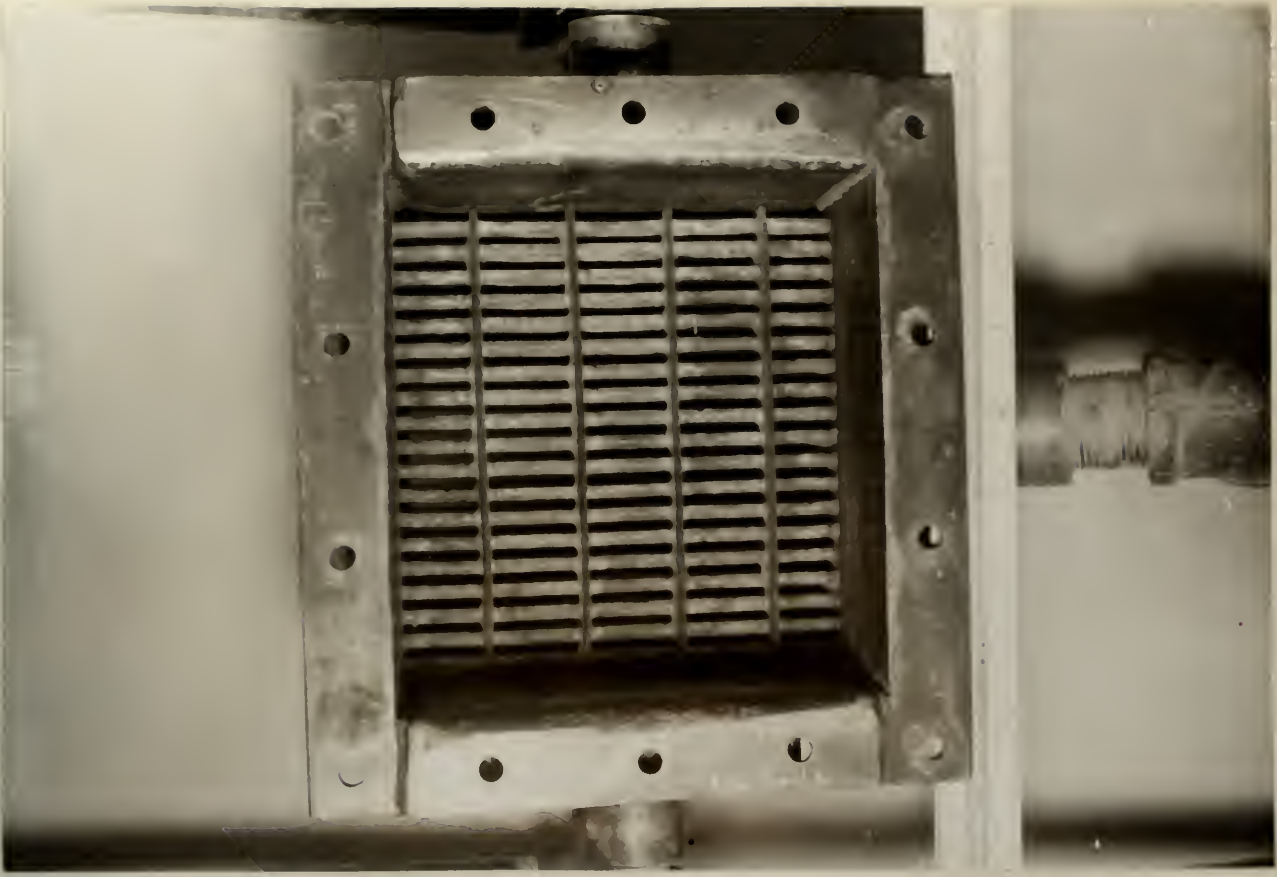
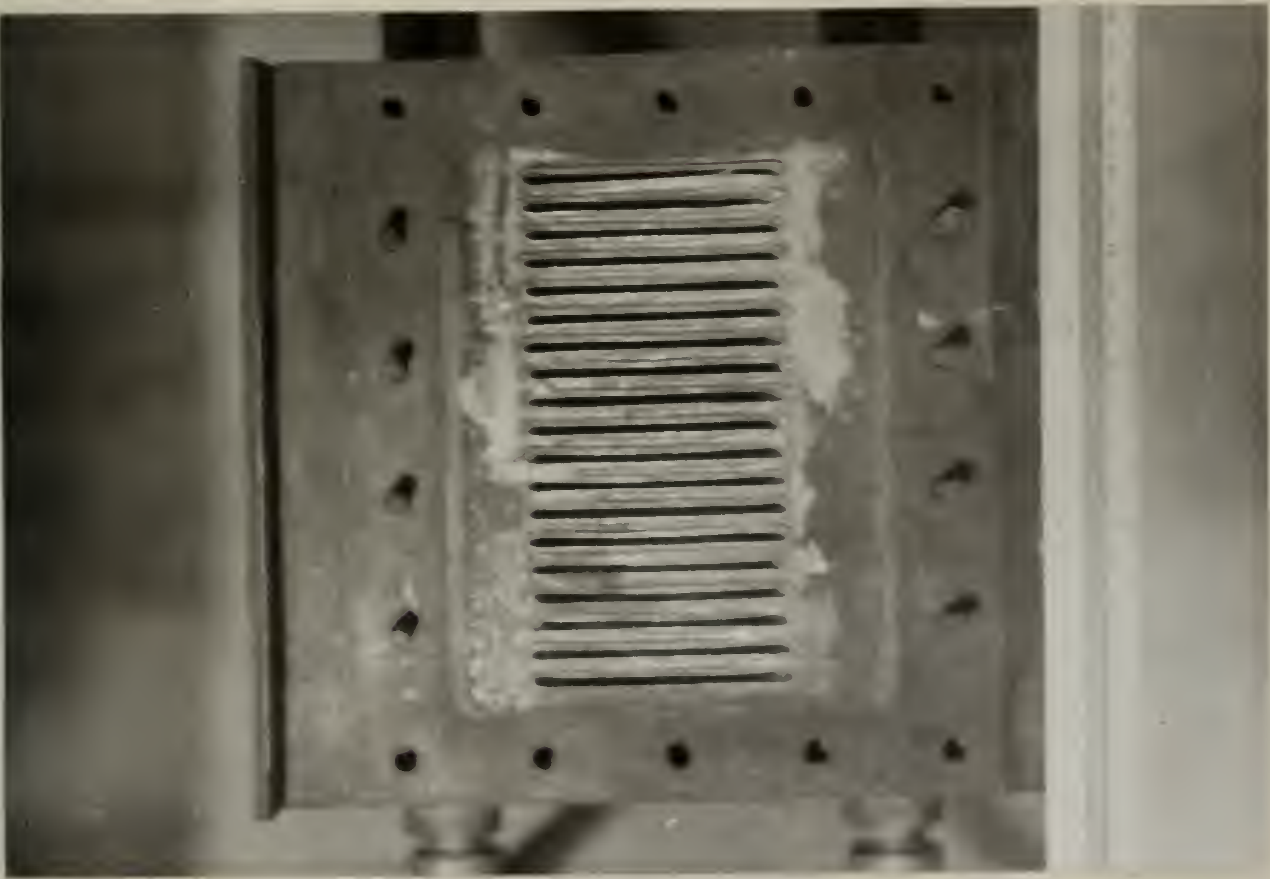


FIG VI



QUENCHING UNIT TUBE SHEET





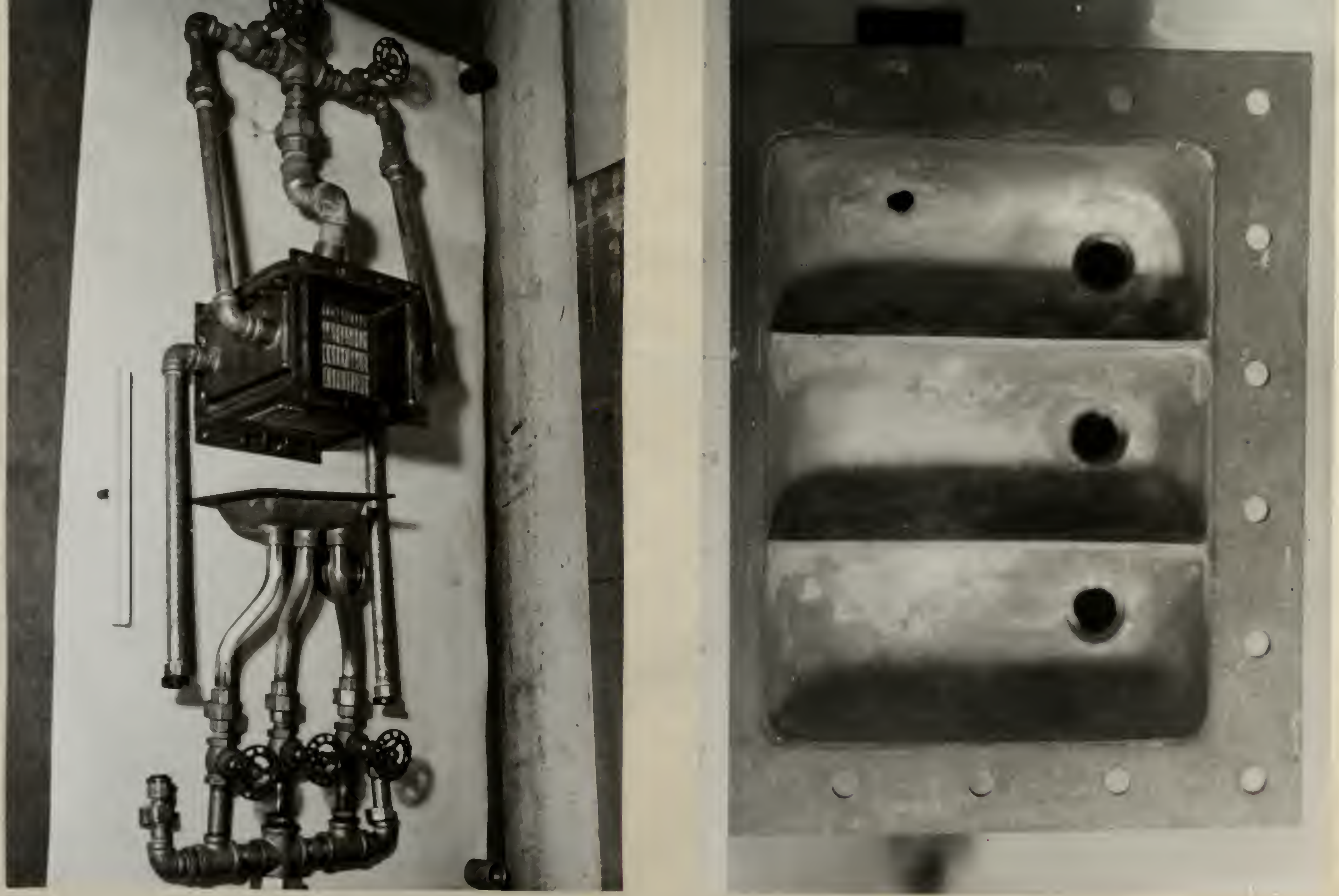
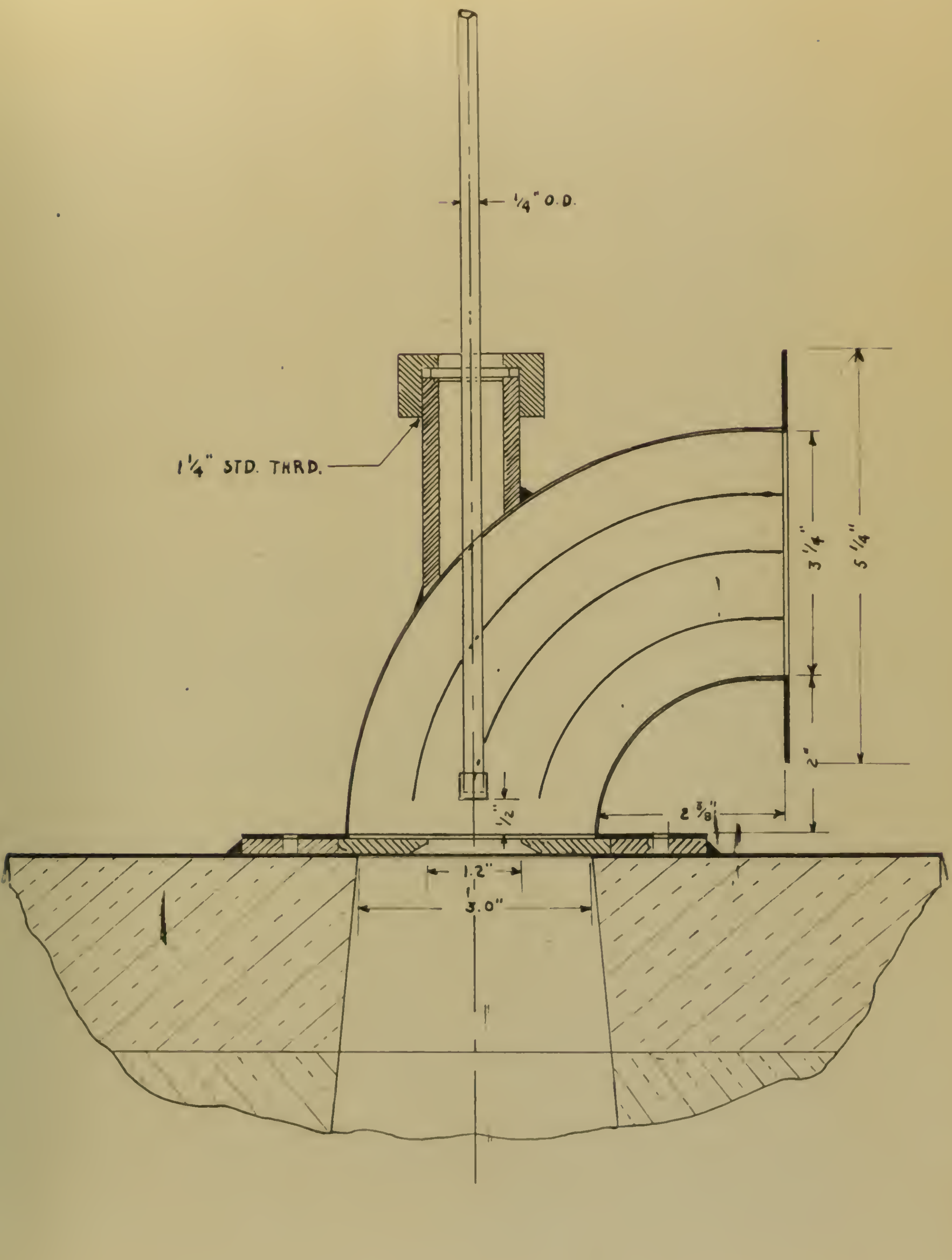


Figure VII
Quenching Unit

FIG. IX

FUEL ATOMIZER ASSEMBLY



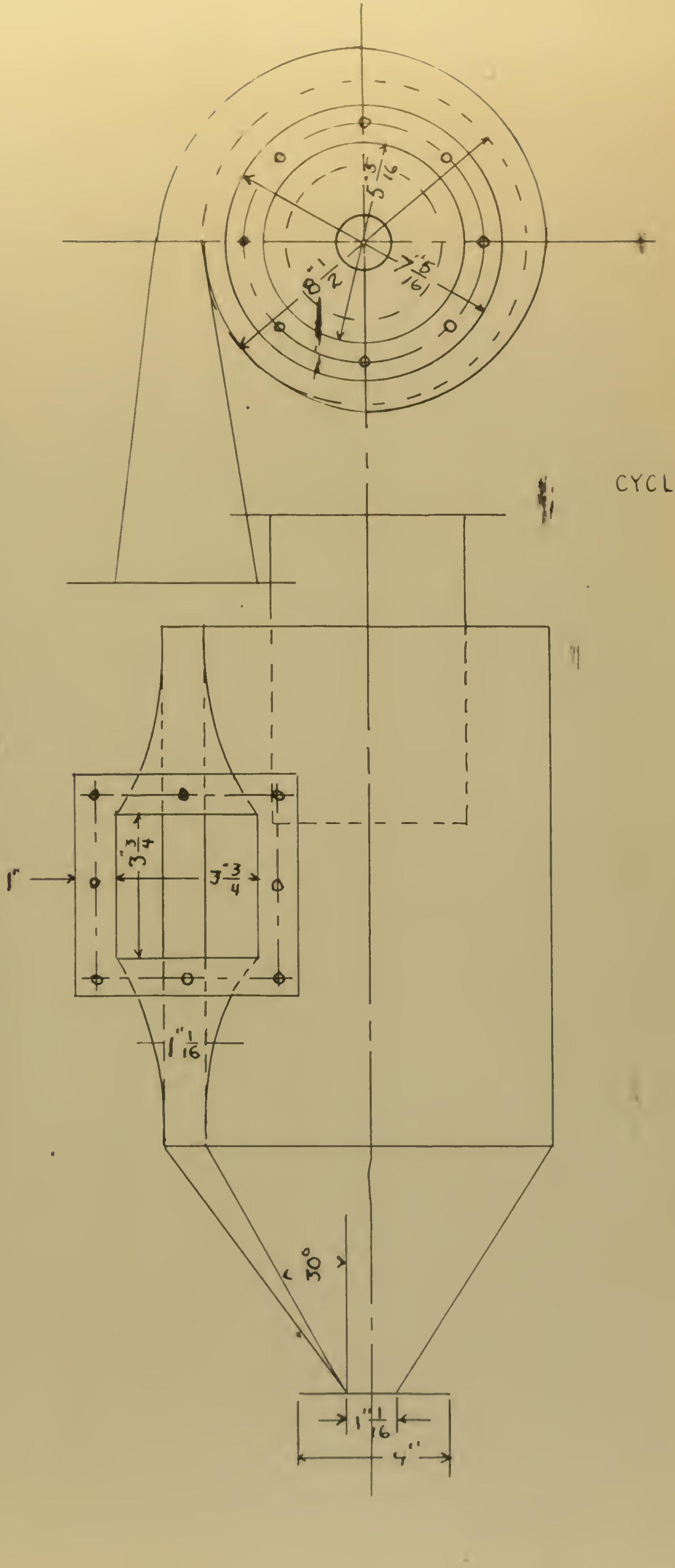


FIG. X
CYCLONE SEPARATOR

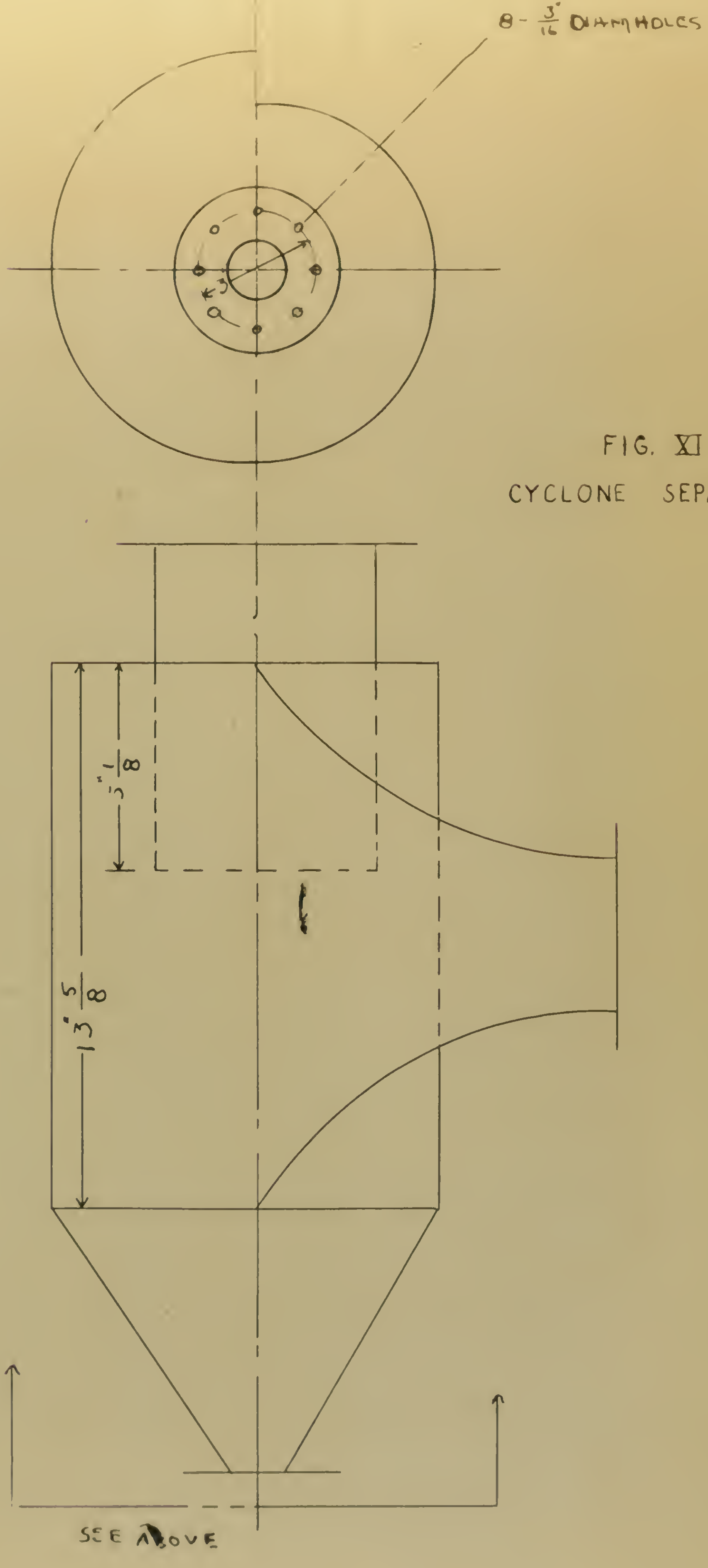


FIG. XI
CYCLONE SEPARATOR

## PROCEDURE

Although the design was based on straightforward calculations, there remained certain unknowns which required investigation by actual test of the equipment. These unknowns were: the drop size, the efficiency of collection by the cyclone separator, and the firing rate for the best combustion. Navy Special fuel oil was selected for the initial runs, made to test the operation of the equipment and to investigate the unknowns.

The preliminary procedure was divided into two parts:

1. The equipment was lighted off using city gas to investigate performance of the various components and to determine what control methods were required for the warm up period. The equipment operated satisfactorily under combustion conditions. The temperature level in the furnace could be controlled quickly by trial and error settings of the gas valves with constant air supply. It was not possible to prevent a rapid rise in temperature of the exhaust gases although this did not cause excessive leakage through the flanges of the quenching unit.

2. This part of the procedure was concerned primarily with trial runs using fuel oil, after warming up the furnace with city gas, to determine the required warm up temperatures, best air-fuel ratios, and relative quantities of solids deposited in the quenching unit, exhaust piping and the separator.

The results of the runs made were more in the form of experience rather than quantitative data. This experience is summarized as follows:

(a) Temperature levels of about 2200°F at the location of thermocouple No. 1 and 1500°F at thermocouple No. 2 could be reached safely after a warm up period of 30 minutes. These levels were satisfactory for oil runs.

(b) The best combustion of fuel oil was obtained using 8 - 40% excess air. If the excess air exceeded 40%, the temperatures did not approach an equilibrium temperature, but decreased continuously. At values lower than 8% the combustion was insufficiently complete.

(c) An appreciable amount of soot and solids was deposited on the tubes of the quenching unit and in the exhaust piping. This necessitated removal of these units for cleaning after each run.

(d) The atomization obtained was representative of that used in industrial furnaces. The particles collected ranged from 0.0006" to 0.006" (approximate). The work of Chang (6) and Gerald (7) shows that for combustion above 1000°C, the diameter of the solid is between 50 and 80% of the original drop size.

(e) Although the efficiency of the separation was unknown, a representative quantity of solids could be collected, i.e. between 0.5% and 0.7% of the weight of the fuel burned.

(f) The fuel rates were not steady during the preliminary runs. This was caused by the method of positioning the fuel

orifice relative to the atomizing orifice. Considerable time was spent in determining the cause of the unsteady oil rates. The time remaining did not permit changing the method of fuel supply to eliminate completely this problem, hence the scope of the investigation subsequently carried out was limited.

The remaining time limited the investigation, and it was decided that the equipment could be used without further modification to compare fuels of a different nature. Any variations of the fuel rate then would permit analysis of the effect of excess air.

The steps carried out in making an actual run were:

(a) The oil sample was weighed and the fuel tank filled. The fuel was then heated to a temperature corresponding to a viscosity of 150 SSU.

(b) Light off furnace and bring up to the temperatures indicated above, using city gas.

(c) Start fuel oil and secure city gas simultaneously. Adjust air supply to the desired quantity. Time of commencement and finish of the fuel-oil run were recorded.

(d) Temperatures were recorded during the period of combustion of fuel oil.

(e) Two gas samples were taken during the run. These samples were taken near the middle of each run.

(f) After the furnace had cooled sufficiently, the soot and solids were removed from the quenching unit, separator,

and the exhaust pipe joining these two units. The weights were recorded and the appearance of the residue was observed under a microscope.

(g) The percentage of unburned carbon in the residue was determined by standard laboratory methods.

## RESULTS AND DISCUSSION

### Performance of the Equipment

The operation of the equipment was satisfactory. There were certain defects in the design that limited the extent of the experimental work carried out in this investigation; and these defects should be eliminated before continuing the work. Combustion was good as is indicated by the gas-analysis. This is an indication that good atomization may be obtained with this equipment at combustion rates comparable to the highest used in forced draft, natural circulation boilers.

The size of the particles and the size distribution law for the atomization is not definitely known, although a qualitative knowledge is available from the sizes of the residues obtained. Chang (6) and Gerald (7) found that above 1000°C, the diameter of the residues formed from single drops was 50 to 80% of the original diameter of the drop. The sizes and distribution of the stack solids found in our runs are shown in the photomicrographs in Figures XIV and XV.

The quenching unit is overdesigned as far as heat transfer is concerned; its reliability is proven for rapid warming-up.

The fuel supply system is not satisfactory. It was possible to obtain a flow rate that was approximately steady, but it was not sufficiently reliable. An unsuccessful attempt was made to make runs with a fuel with a pour point of 110°F. This difficulty can be eliminated by using a small gear pump with provisions for recirculating to obtain the desired flow rate.

It is also recommended that a different method be used for lighting off because of the back draft always present in the building where the equipment is located. It is possible to install a glow plug that can be retracted into the refractory after the furnace has been lighted off with city gas.

The results of the gas sampling are not consistent with the results from metering of the air. This discrepancy was probably caused by the flow pattern in the exhaust piping from the cyclone separator. Vortex flow exists in the exhaust piping from the separator. This permits vertical circulating currents and since the stove piping comprising this exhaust line is not air-tight, it is a possible source of leakage. However, the values of the H/C ratio found from the gas analysis should be consistent and correct. It is recommended that a screen be installed in the exhaust piping to straighten out the flow or that the sampling tube be installed in the piping between the quenching unit and cyclone separator.

The actual efficiency of collection of the cyclone separator is not known. However, it's efficiency seems adequate for relative results. Before the investigation is continued, the efficiency should be determined so that the amount of solids collected may be used to determine the actual amount of stack solids formed, rather than a relative amount. It is suggested that a part of the gas leaving the separator be passed through a suitable filter to determine the amount of stack solids which are not collected in the separator.

The time required for making a run, cleaning and reassembling the quenching unit, separator, and exhaust piping is ap-

proximately six hours. The cost of the oil burned per run is negligible. The installation cost is relatively low in comparison with that of other investigators who have used installations which burned as much as 600 lbs. of fuel oil per hour. This equipment permits an economical study of the factors that influence the formation of stack solids, and an investigation of the effects of additives on the quantity of stack solids formed.

## Data from Combustion of Fuel Oil

It was not possible to make enough runs to permit a rigorous analysis of the factors affecting the formation of stack solids. The data does establish the direction of the variation for two of the variables that were studied. A summary of the results and calculations of the runs made is presented in Table I.

Runs #2 and #3 were made with conditions as nearly the same as possible. The results are close enough to indicate that a run is reproducible with the equipment. The design of the equipment is such that the cleaning of the components is simple and the variation due to different degrees of cleanliness is negligible. Some scatter in the results must be expected since the furnace is not an isothermal one. Instead an effort is made to reduce the time required for a run, permitting some variations in the temperature level. Other variations in temperature level must be expected when the firing rate is changed. The results of the runs are considered good.

The effect of the nature of the fuel is shown by comparing

## TABLE I

## SUMMARY OF DATA AND CALCULATIONS

| RUN NO. | FUEL |  |  | EXCESS AIR ** |  | H/C RATIO | MEAN TEMPERATURE |  |  | SOLIDS COLLECTED |  |  |  |  |  | TOTAL SOLIDS |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | TYPE | WEIGHT LBS. | RATE LBS. / HR | METER % | GAS ANALYSIS % | GAS ANALYSIS | THERMOCPL. #1 °F | THERMCPLE. #2 °F | THERMCPLE. #3 °F | QUENCH. UNIT LBS. | QUENCH. UNIT %-FUEL | EXHAUST PIPE LBS. | EXHAUST PIPE % FUEL | SEPARATOR LBS. | SEPARATOR % FUEL | LBS. | %-FUEL |  |
| 1 | NAVY SPECIAL | 7.65 | 14.82 | 8.33 | 7.0 | 1.76 | 2362 | 1810 | 1115 | 0.0233 | 0.306 | 0.0121 | 0.158 | 0.0218 | 0.285 | 0.0572 | 0749 |  |
|  |  |  |  |  |  |  |  |  |  | * 53.09 |  | * 82.02 |  | * 83.27 |  | * 70.69 |  |  |
| 2 | COMMERCIAL BUNKER "C" | 8.25 | 15.00 | 7.07 | -0.12 | 1.60 | 2446 | 1985 | 1080 | 0.0299 | 0.363 | 0.0449 | 0.545 | 0.0570 | 0.691 | 0.1318 | 1.599 |  |
|  |  |  |  |  |  |  |  |  |  | * 49.81 |  | * 88.04 |  | * 84.39 |  | * 77.78 |  |  |
| 3 | COMMERCIAL BUNKER "C" | 8.81 | 15.12 | 6.25 | 21.6 | 1.63 | 2505 | 2200 | 1060 | 0.0240 | 0.273 | 0.0475 | 0.541 | 0.0581 | 0.661 | 0.1296 | 1.475 |  |
|  |  |  |  |  |  |  |  |  |  | * 44.12 |  | * 87.20 |  | * 89.09 |  | * 80.08 |  |  |
| 4 | NAVY SPECIAL | 8.40 | 12.00 | 34.20 | 28.7 | 1.76 | 2205 | 1715 | 1000 | 0.0128 | 0.152 | 0.0053 | 0.063 | 0.0101 | 0.121 | 0.0282 | 0.336 |  |
|  |  |  |  |  |  |  |  |  |  | * 39 00 |  | * 58.94 |  | * 78.67 |  | * 56.95 |  |  |
| 5 | NAVY SPECIAL | 8 45 | 12.96 | 40.00 |  |  | 2270 | 1990 | 1030 | 0.0145 | 0.172 | 0.0022 | 0.026 | 0.0161 | 0.191 | 0.0328 | 0.389 |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
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|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

* UNBURNED CARBON — PERCENT OF SOLIDS

** DISCREPANCY IN GAS ANALYSIS DUE TO AIR LEAKAGE

Run #1 with Runs #2 and #3. The commercial Bunker "C" oil formed approximately twice the amount of stack solids as the Navy Special. These runs were made under the same conditions of atomization and at the same air rate. The solid forming tendency of the oil is probably indicated by some property of the fuel oil. It is interesting to compare the asphaltine content and the Conradson carbon tests for the oils concerned. It is recommended for further investigation that two oils be used for the study, one, with low asphaltine content and tendency to form stack solids, and two, a fuel with high asphaltine content and high stack solid forming tendencies. The intermediate points could be obtained by blending the two fuels.

The effect of the amount of excess air is indicated by Runs #1, #4, and #5. The trend indicated here is not a simple function and proper presentation of the results is necessary for "the effect of excess air" to have a meaning.

The percentage of excess air may be varied in two ways, the oil rate may be varied with air rate constant, or the air rate may be varied with oil rate constant. Either method causes a decrease in the temperature level in the furnace for increasing excess air, and this variation must be accepted as long as an isothermal furnace is not used.

If the excess air is varied by varying the air rate, there is an additional effect which is important in the subject problem. This is a change in the combustion time or the time in the furnace. The average time in the furnace may be expressed

approximately as the quotient, Furnace Volume / Volume Flow rate of the products at the mean furnace temperature. If the flow rate for an 8% excess air run is 52 cu. ft./min., and the excess air is increased to 35% by varying the air rate, it is necessary to increase the air rate to 64.8 cu. ft./min. This will reduce the combustion time to 52/64.8 or 0.802 of the original value. Since the combustion of the residues takes place by the slow process of heterogenous combustion, a decrease of time in the furnace should have a large effect on the quantity of solids formed.

If the amount of excess air is varied by controlling the fuel rate with the air rate kept constant, the change in combustion time is negligible.

In the absence of enough data to establish definitely the complete picture it was desirable to compare the results obtained with those of other investigators. The results of an investigation by an oil company were selected, and are reproduced in Table II. These results are reduced to fuel and air rates per hour per cu.ft. of furnace volume, so that they may be compared with the results of this investigation on one plot. The data of the oil company is plotted in Figure XII and the results of this investigation are superimposed in red. The results of this investigation have been reduced to the same basis as the oil company's data. Those values are given in Table III. The vertical lines represent lines of constant approximate combustion time. The horizontal lines represent lines of constant fuel rate. Lines of equal percentage of stack solids have been faired in as well as possible from the oil company's data, and

## TABLE II

## DATA FROM TESTS BY AN OIL COMPANY USING A HEAVY FUEL OIL

| Run No. | Oil Rate #lb/hr. | Equiv.Excess Air % | Total Stack Solids | Oil Rate* lb/hr-cu. ft.furn.vol. | Air Rate* lb/hr.cu. ft.furn.vol. |
|---|---|---|---|---|---|
| 1 | 230 | 72 | 0.50 | 1.21 | 31.2 |
| 2 | 219 | 98 | 0.81 | 1.152 | 34.25 |
| 3 | 238 | 216 | 2.49 | 1.253 | 59.40 |
| 4 | 268 | 132 | 0.87 | 1.412 | 49.10 |
| 5 | 283 | 180 | 1.53 | 1.49 | 62.60 |
| 6 | 278 | 225 | 2.77 | 1.464 | 71.40 |
| 7 | 421 | 23 | 0.43 | 2.22 | 41.00 |
| 8 | 414 | 73 | 0.88 | 2.18 | 56.60 |
| 9 | 441 | 105 | 1.22 | 2.32 | 71.30 |
| 10 | 400 | 115 | 1.46 | 2.105 | 67.90 |
| 11 | 528 | 23 | 1.24 | 2.78 | 51.30 |
| 12 | 548 | 49 | 1.63 | 2.89 | 64.60 |
| 13 | 694 | 21 | 1.86 | 3.65 | 66.30 |

* Computed values using a furnace volume of 190 cu.ft. and assuming an air rate of 15 lb. air per lb. fuel for theoretical complete combustion

## TABLE III

## EXPERIMENTAL DATA AS PLOTTED IN FIGURE XII

| Run No. | Fuel Rate lbs/cu.ft.-hr | Excess Air % | Air Rate* lbs/cu.ft.-hr | Total Stack Solids % |
|---|---|---|---|---|
| 1 | 8.52 | 8.33 | 138.4 | 0.749 |
| 2 | 8.62 | 7.07 | 138.4 | 1.599 |
| 3 | 8.69 | 6.25 | 138.4 | 1.475 |
| 4 | 6.90 | 34.2 | 138.4 | 0.336 |
| 5 | 7.45 | 40.0 | 156.5 | 0.389 |

* Theoretical air assumed to be 15 lbs. air per lb. of fuel.

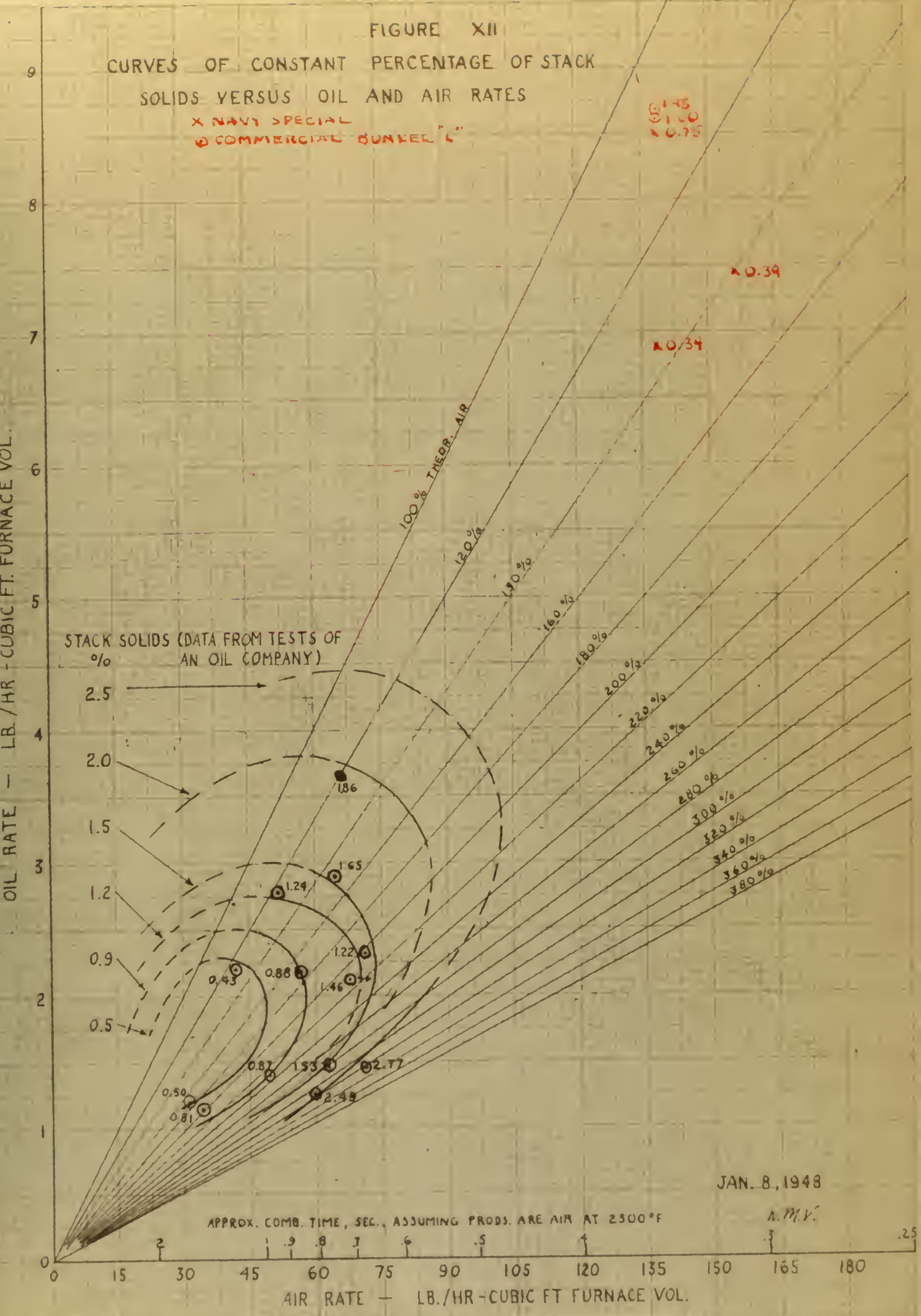


FIGURE XII

CURVES OF CONSTANT PERCENTAGE OF STACK SOLIDS VERSUS OIL AND AIR RATES

JAN. 8, 1948

R.M.V.

these curves appear to be contours. There is a definite optimum value of firing rate and air rate for a given furnace and a given fuel. Similarly, if either an air rate or a fuel rate is selected, there is an optimum value for the other rate. These statements refer to the stack solid problem only and neglect the economy of combustion.

When presented on this plot, the results obtained in Runs #1, #4, and #5 indicate that the equipment was operated under conditions which lie on the upper branch of the family of curves for the furnace and the given oil. The results are consistent with the expected variation when compared with the data from the oil company's investigation. If any point is selected on the upper branch of a curve and the fuel rate is decreased along a line of constant air rate, the quantity of stack solids should decrease until the minimum for that air rate is reached. This is analogous to the variation between Runs #1 and #4. Run #5 was one of the preliminary runs made to test the equipment. It has been included on the plot, and it indicates further the consistency with the other data. It should be noted that it is made with a higher air rate. No gas samples were made during the preliminary runs.

These results suggest a procedure for the continued investigation of the problem. Several different air rates should be selected and fuel rates varied over as wide a range as possible.*

* These investigators experienced difficulty in runs with a fuel rate of 0.18 lb/min and an air rate of 58.8 cu.ft./min. Under these conditions the residue deposited in the quenching unit is sticky; this prevents thorough cleaning and accurate determination of the weight of residue. There is probably a lower limit for fuel rate with each air rate. This may require a further increase in furnace length.

Curves of stack solids versus fuel rate may be plotted for constant air rates, and from this family of curves points may be obtained to construct a plot such as shown in figure XII.

The carbon content of the residues increases as the weight percent of the stack solids increases. This is expected from the theory of combustion proposed by Chang (6) and Gerald (7). The process of heterogeneous combustion is aided by increasing the excess air, and therefore the percent of unburned carbon should decrease. The commercial bunker "C" has a lower H/C ratio which indicates a greater percentage of the heavier hydrocarbons and non-volatiles, hence a greater percentage of residue that must burn by heterogeneous combustion.

## Visual Observations

The appearance of the residues collected were observed under a microscope. In general there was no difference in physical appearance of the solids collected from the same place in the equipment for different runs. The solids collected from the exhaust pipe and the cyclone separator were well defined shapes; the majority of the particles were compact spherical coked particles with a dimpled surface. Other than these, there was a small percentage of cenospheres, burned out frame works of both of these types, and an occasional soot string. The solids collected from the quenching unit did not have a well defined shape but seemed to be composed primarily of soot masses with many smaller coke spheres intermixed.

It was interesting to note that the unburned content of the residue from the quenching unit was less than that collected in the exhaust pipe and the separator. The number of cenospheres formed was greater for the runs with the greater percentage of excess air.

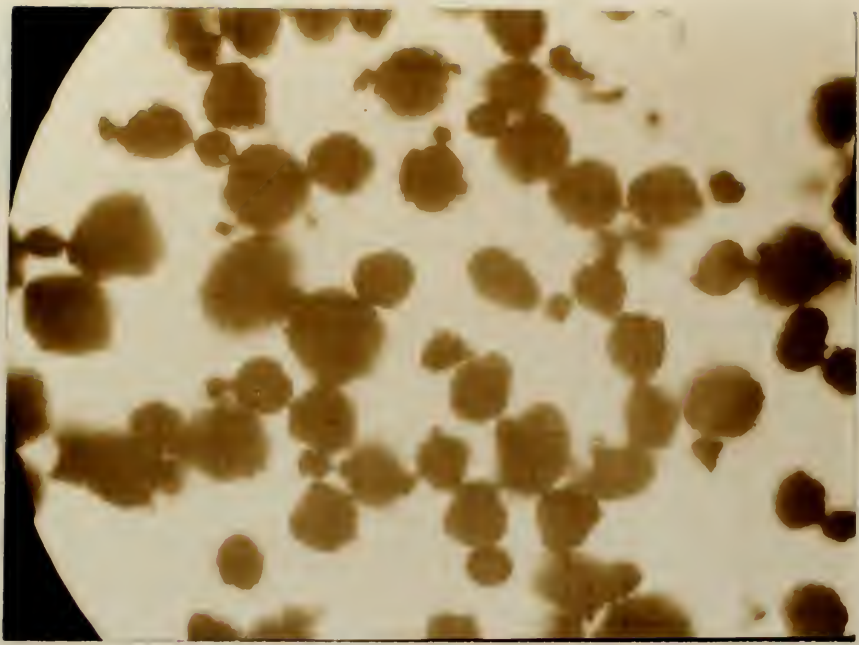
There are several photomicrographs in the following figures which show the representative types of residues, sizes and distribution of sizes.

Two sight glasses were provided for observation of the combustion processes. The location of these sight glasses is shown in Figure I. It was interesting to note that in the upper sight glass the first luminosity of the flame appeared as flashes. At the second sight glass, located at about mid-length, the particles appeared as luminous parallel streaks; luminous flames were also visible that eddied at random through the streaks.

Figure XIV

Residues, Showing Sizes and Distribution

Magnification 170X



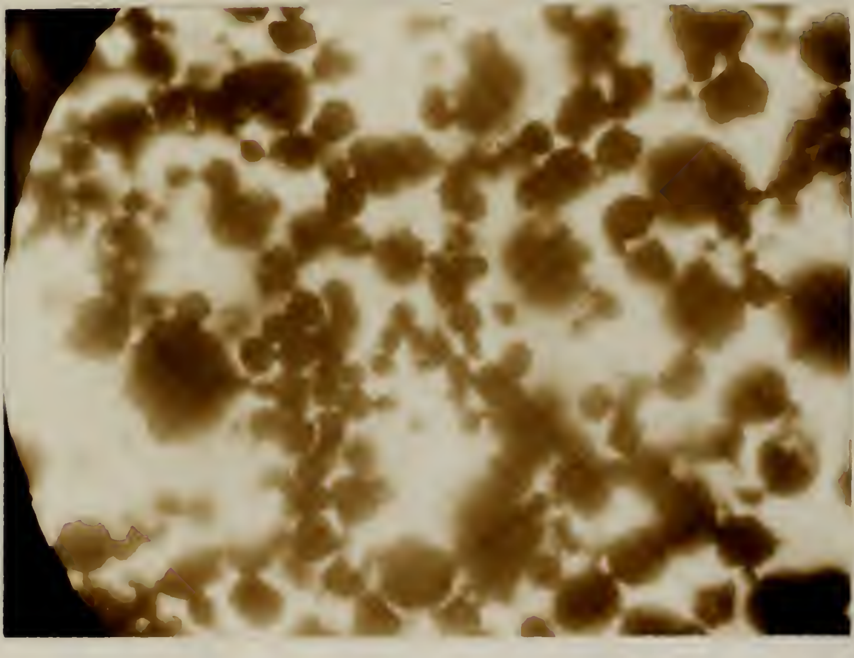


Figure XV

Residues, Showing Sizes, Distribution and Types

Magnification 420X

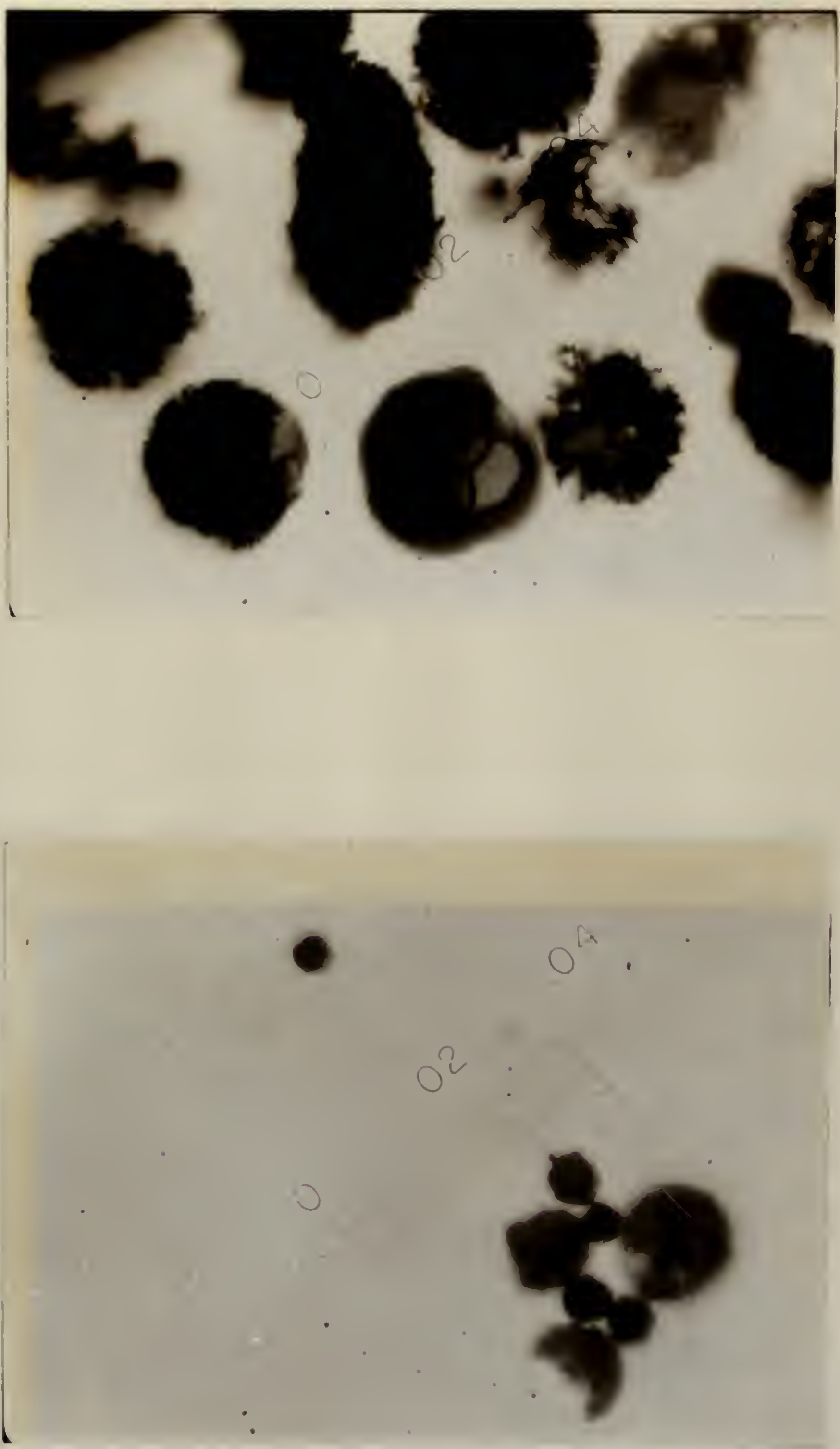
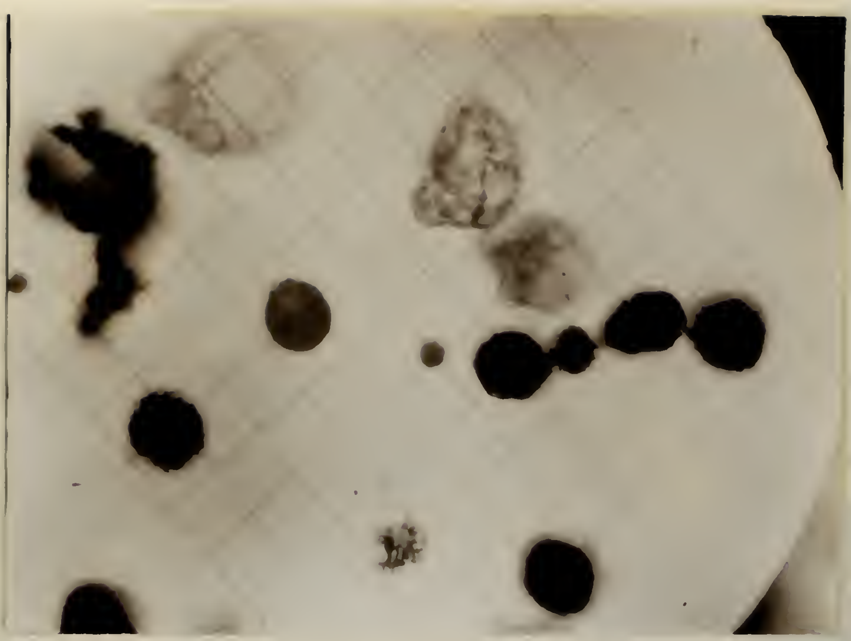


Figure XVI

Types of Residues

Magnification 170X



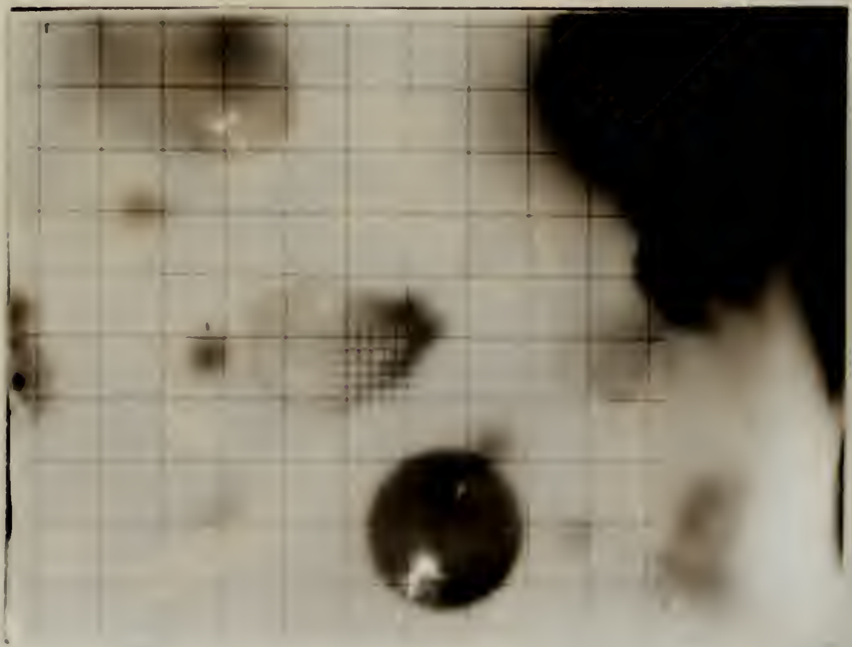
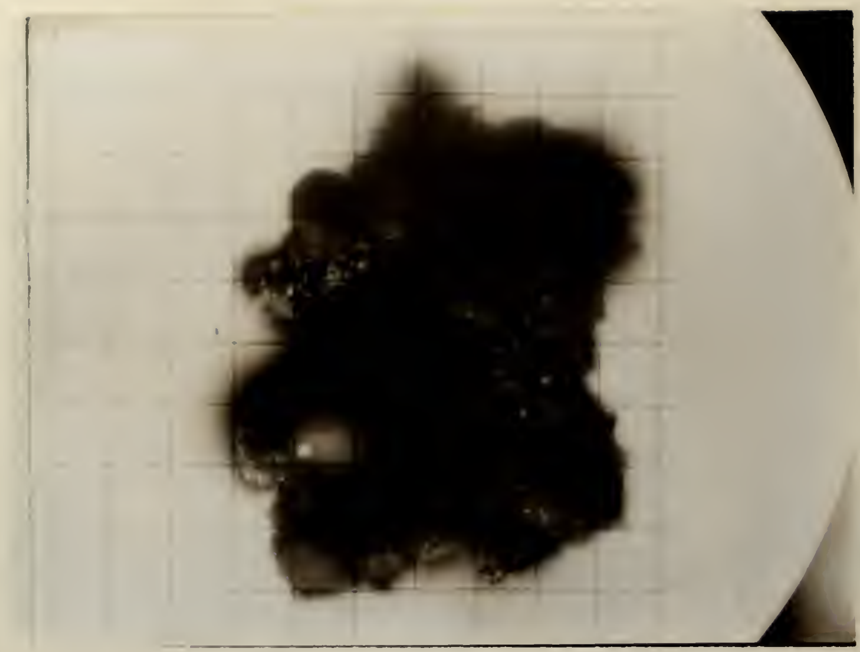


Figure XVII

Types of Residues

Magnification 170X



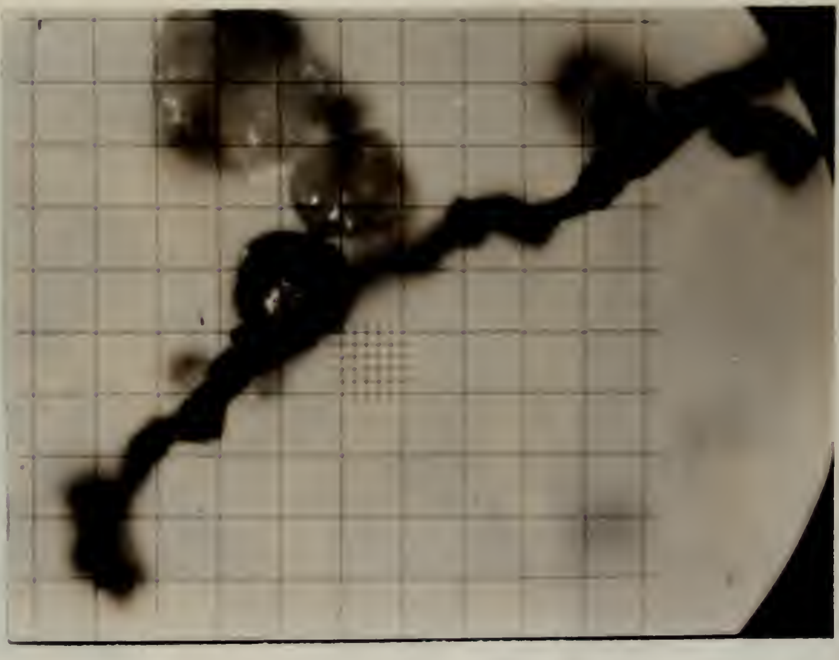
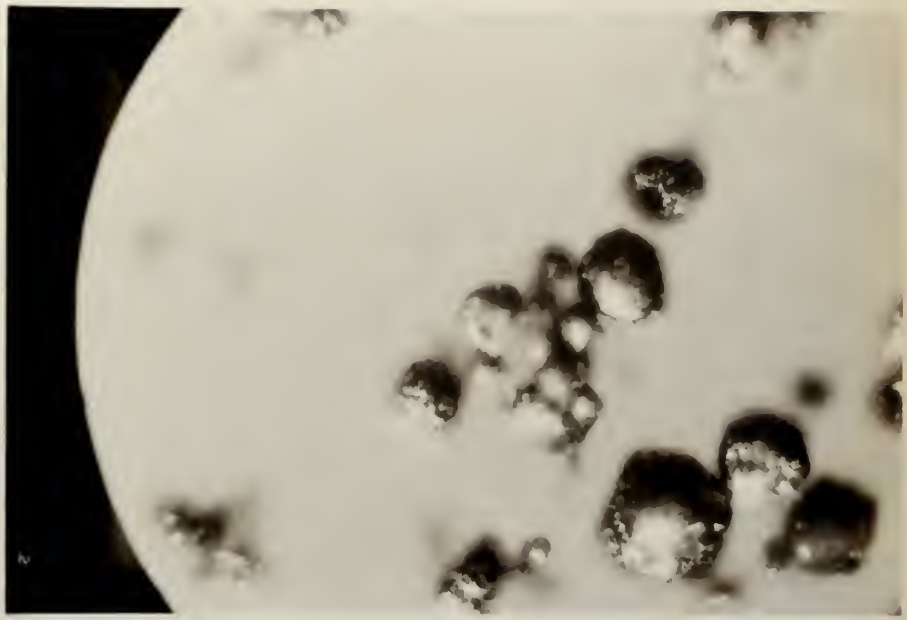


Figure XVIII

Types of Residues

Magnification 170X



Magnification 105X

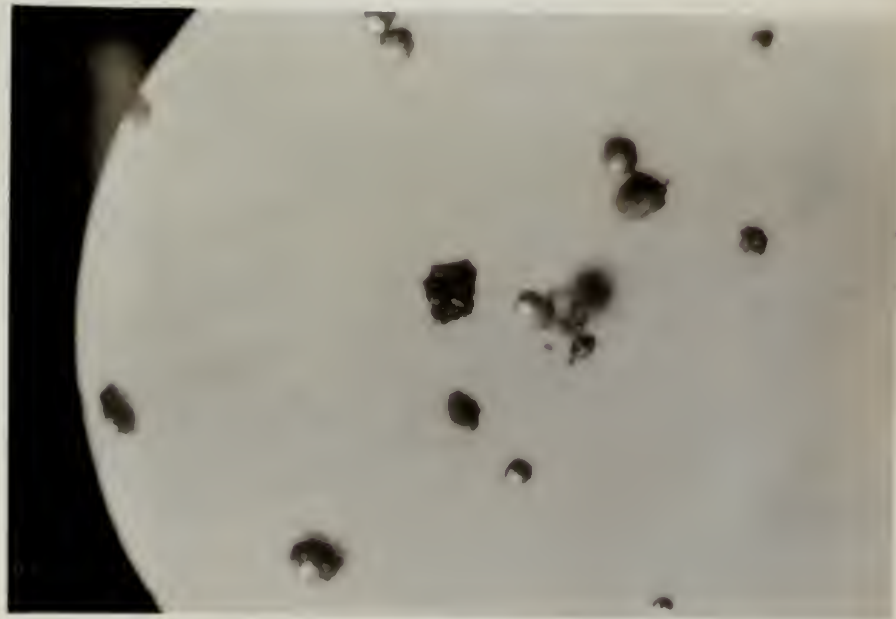
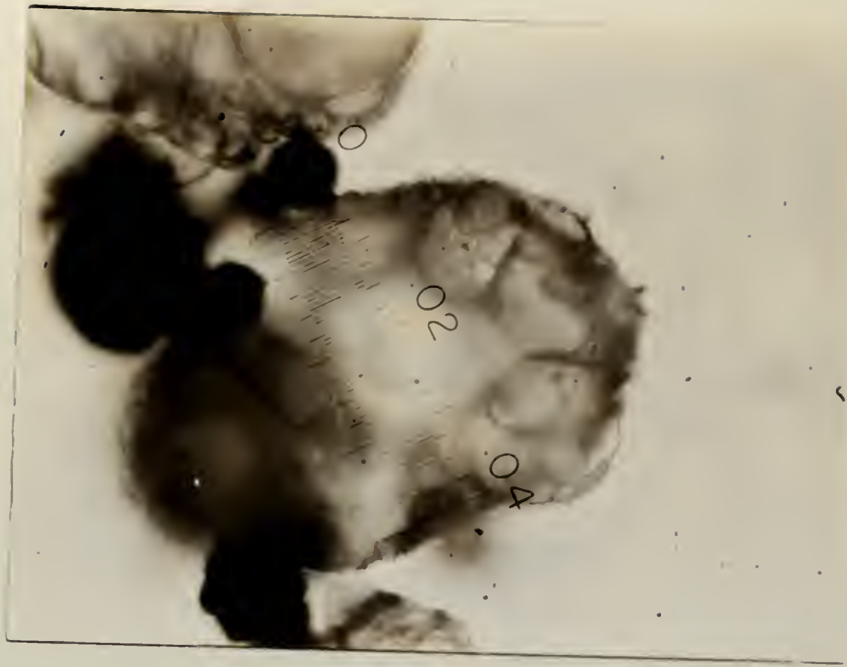


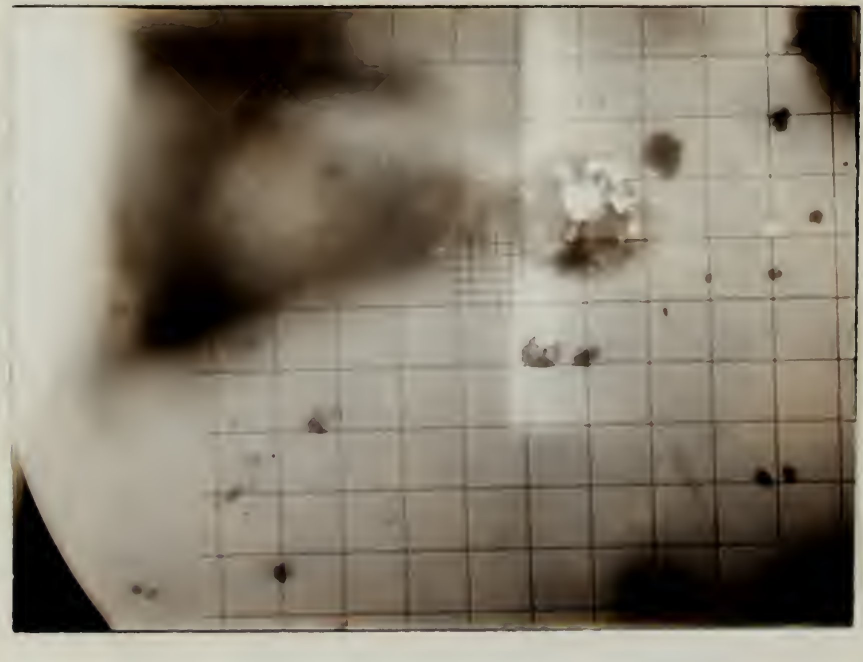
Figure XIX

Types of Residues

Magnification 420X



Magnification 170X



## CONCLUSIONS

1. The equipment operates satisfactorily, i.e. good combustion is obtained at high firing rates. It is possible to investigate the effect of excess air or furnace atmosphere and the nature of fuel oils on the formation of stack solids.
2. The equipment represents an economical and rapid method of investigating the factors influencing the formation of stack solids.
3. The results obtained are consistent with the results of other investigators.
4. The nature of the fuel oil is an important factor. This is probably indicated by some property of the fuel, such as the asphaltine content, Conradson Carbon Test, or the H/C ratio. The fuels studied indicate the solids increase as the asphaltine content increases and as the H/C ratio decreases.
5. A new method of presenting the data is suggested to show more exactly the effect of excess air. The latter may be varied by controlling the fuel rate or the air rate. The results have a meaning which depends on the method used with a specific furnace.
6. The results obtained for variations in excess air are consistent with data obtained by other investigators.
7. In a given furnace there is an optimum value of firing rate and air rate for a minimum formation of stack solids. This optimum value depends on the type of fuel used.

8. In a given furnace there is an optimum air rate for a fixed fuel rate at which the stack solids formed will be a minimum for the particular heavy fuel oil used.
9. In a given furnace, for a fixed air rate, there is an optimum value for the fuel rate at which the solids formed will be a minimum for the particular heavy fuel oil used.
10. The unburned carbon content of the stack solids increases as the weight percent of stack solids increases.
11. The appearance of the residues substantiates the combustion theory proposed by Chang (6). The character of the solids is quite varied and seems to be caused by conditions inherent in the combustion of clouds of non-uniform particles.
12. The Stack solids are composed of: (1) dimpled, compact spherical coked particles, (2) cenospheres, (3) burned out frame works of the first two, and (4) strings of soot and soot masses.

# RECOMMENDATIONS

1. The fuel supply should be changed to permit accurate control of the fuel rate, and to permit handling of high pour point oils.
2. The method of atomization should be studied to ascertain the drop size and the size distribution law.
3. The efficiency of the separating unit should be determined.
4. The method of lighting off should be changed to simplify this operation.
5. A thorough investigation of the nature of the fuel oil should be conducted. The asphaltine content, the H/C ratio, and Conradson Carbon Test are properties that should best indicate the stack solid forming properties.
6. The excess air is an important factor in the formation of stack solids. Further investigations should be made with constant air rates and varying fuel rates. The results should be presented in the manner suggested, the final result being a plot such as Figure XII.
7. The optimum values for minimizing stack solids should be compared with optimum economic values.
8. A thorough investigation of the effect of additives on the amount of stack solids formed should be made.

# APPENDIX

## SUPPLEMENTARY INTRODUCTION

The method of atomization used was studied by Nukiyama and Tanasawa (10). Experiments were conducted using a sharp-edged orifice similar to the atomizer assembly shown in Figure IX. The air pressures used were not high enough to use compressible flow equations.

The velocities were based on the cross-section at issue, and the term relative velocity was used. A discharge coefficient of 0.64 is used when a sharp-edged orifice is used for the air.

$$V_{rel.} = \frac{Q_a}{\frac{\pi}{4} 0.64 D_a{}^2} - \frac{Q_F}{\frac{\pi}{4} D_F{}^2}$$

The results indicate the mean drop diameter formed is a function of the fuel-air ratio and the relative velocity. For air-fuel ratios above $Q_a/Q_F = 5{,}000$ the drop diameter depends on the relative velocity only.

They determined a size distribution law that fitted their data moderately well when the air velocity exceeded 150 meters/second and for $Q_a/Q_F$ greater than 5,000. This distribution law was:

$$\frac{d_n}{d_x} = a x^p e^{-b x^q}$$

where p equals 2 and q equals 1.

The mean drop size was that diameter having the same ratio of volume to surface as the whole sample.

Allowance for surface tension and viscosity was made and the result was

$$d_0 = \frac{585\sqrt{\sigma}}{V_{rel}\sqrt{\rho}} + 597\left(\frac{\mu}{\sqrt{\sigma\rho}}\right)^{0.45}\left(1000\,\frac{Q_F}{Q_A}\right)^{1.5}$$

where $d_o$ = drop diam., microns          $\sigma$ = dyne / cm.

$\rho$ = gm/cm$^3$          $\mu$ = dyne sec/cm$^2$

$V_{rel}$ = meters/sec

For heavy oil ($\rho = 0.9, \sigma = 29, \mu = 0.5$):

$$d_o = \frac{3320}{V_{rel}} + 210\left(1000\,\frac{Q_F}{Q_a}\right)^{1.5}$$

It was not practicable to use pressure atomization because of the large cone angles inherent in this method. With the small cross-section selected, wall impingement would have presented a serious problem. The air atomization as outlined above was particularly well suited to the investigation for several reasons:

1. The particle size may be varied with a constant fuel-air ratio by changing the size of the atomizing orifice.
2. The fuel rate may be varied without appreciable effect on the particle size.
3. The air rate may be varied without affecting particle size by proper selection of atomizing orifice size.

Because of the limited capacity of the blower available for the investigation, and to obtain drop diameters approximating those obtained by pressure atomization in commercial practice, it was necessary to operate in the range below the lower limit prescribed by the size distribution law. This required that the quality of atomization obtained with the equipment be determined.

## DETAILS OF PROCEDURE

### Design Procedure

It was desired to design a furnace which would approximate the firing rates of naval and industrial units, and at the same time be of such a size and construction as to lend itself to experimental work. With this in mind, the following limitations were set:

1. Fuel rate to be two gallons per hour.

2. Combustion rate to be 170,000 BTU's per hour per cubic foot of furnace volume.

3. Furnace to be long and narrow with a square cross-section 5.5 inches on a side. This is convenient for determining mean time of particles in the furnace, and permits a simple construction.

4. A quenching unit would be installed at the exit of the furnace to stop combustion in as short a space as possible.

5. A cyclone separator would be used to collect solids in order to minimize pressure drops.

With a fuel of an assumed analysis typical of heavy fuel oils, the air rate was determined to give 13.5% $CO_2$ in the combustion products. Under these conditions, the $\Delta H$ of combustion was determined. For details of this computation see the sample calculations.

Using this value of $\Delta H_C$, a furnace volume was computed to give the desired firing rate. With this volume and a given cross-section, it was possible to compute the length of the furnace.

A theoretical flame temperature was then computed, assuming complete combustion. Next, the furnace losses were computed assuming the external losses to be equal to the convection to the refractory. This determined the furnace exit temperature.

The design of the quenching unit was based on cooling combustion products from 2740 F to 1500 F. Narrow, deep, thin-walled tubes were used to provide as large a heat transfer area as possible with minimum resistance, and to keep deposits of stack solids on the unit to a minimum. Although it was not possible in such a small unit to provide the amount of heat transfer surface computed, it was decided to use this design in belief that actual furnace temperatures would run lower than the computed temperatures, and because the water cooled walls and headers would carry away an undetermined amount of heat. This decision was subsequently justified by the results obtained from this unit.

## Lighting Off Procedure

The fuel supply tank and feed line were removed for cleaning and filling before starting a run. For lighting off, a gas jet was inserted into the fuel supply line opening in the elbow; this jet extended through the atomizing orifice. The jet was lighted and inserted, the side jets opened and the blower started immediately. The amount of gas to the side jets was reduced to the minimum by almost closing the valves; the lighting off jet was secured and retracted into the elbow to reduce the resistance to the air flow. The air supply was ad-

justed to maximum flow.

As soon as the bricks were hot enough to relight the city gas, all gas to the unit was cut off, the lighting off jet removed, and the fuel tank placed in the position for a run, and the fuel was heated to the temperature corresponding to a viscosity of 150 SSU. The city gas to the side jets was cut on again and the furnace temperatures were brought to the desired level by trial and error settings of the gas valves. The fuel oil supply valve was opened wide and the city gas immediately secured.

## Fuel Rate

The fuel oil was weighed to the nearest gram on a 5.5 kilogram balance.

## Fuels Studied

The fuels used were Navy Special fuel oil and a commercial Bunker "C" fuel of moderate stack solid forming tendencies. The properties of these fuels were as follows:

| | Navy Special | Commercial Bunker "C" |
|---|---|---|
| API Gravity | 20.0 | 14.4 |
| Viscosity SSF at 122°F | 18 | 143 |
| Flash Point (PM) | 180°F | 170°F |
| Pour Point | 0°F | 20°F |
| Insoluble % in 86° Naptha | 4.18 % | 8.97 % |
| Conradson Carbon | 5.66% | 9.54% |
| Relative Stack Solids | | 1.0* |

| | Navy Special | Commercial Bunker "C" |
|---|---|---|
| % by weight | | |
| C | 85.7 | |
| H | 11.4 | |
| O | 0.9 | |

*Furnished by private communication. No comparative data is available for the other oil.

## Photo-micrographs of Residues.

Photo-micrographs of some typical residues were taken at about 170 X and 420 X by putting a Leitz microcamera in place of the eye piece of a microscope. The pictures were taken with background and/or oblique top lighting.

## Residues.

The residues collected were weighed to the nearest tenth of a gram.

## Summary of Original Data and Calculations

Run 1:

Fuel - Navy Special

Fuel temp (150 SSU) - 137°F

Quantity burned - 7.65 lb.

Time - 31 min.

Rate - 0.247 lb/min.

Average Air Temperature (Blower Discharge) - 100F

Air Supplied - 52.0 cu.ft./min. (50 MM $H_2O$)

Excess Air (Meter) - 8.33%

Excess Air (Gas Analysis) - 7.0%

H/C ratio - 1.76

Temperatures (°F):

| Time (Min.) | TC1 | TC2 | TC3 |
|---|---|---|---|
| 00 | 2295 | 1525 | 1145 |
| 03 | 2165 | 1605 | 1095 |
| 09 | 2235 | 1695 | 1095 |
| 19 | 2341 | 1945 | 1105 |
| 25 | 2430 | 2095 | 1136 |

Stack Solids:

| Source | Weight grams | % of Wt. of Fuel Burned | Unburned Carbon-% |
|---|---|---|---|
| Quenching unit | 10.6 | 0.306 | 53.09 |
| Exhaust Pipe | 5.5 | 0.158 | 82.02 |
| Separator | 9.9 | 0.285 | 83.27 |
| Total | 26.0 | 0.749 | 70.69 |

Gas Analysis:

$CO_2$ - 13.3%

$O_2$ - 2.14

$H_2$ - 0.32

CO - 1.07

$N_2$ - 83.17

100.00

## Run 2:

Fuel - Commercial Bunker "C"

Fuel temperature (150 SSU) - 205°F

Quantity burned - 8.25 lb.

Time - 33 min.

Rate - 0.250 lb/min.

Average Air Temperature - 100°F

Air Rate - 52.0 cu.ft./min. (50.0 "W $H_2O$)

Excess Air (Meter) - 7.07%

Excess Air (Gas Analysis) - 0.12% deficiency

H/C ratio ( " " ) - 1.60

### Temperatures (°F):

| Time (Min.) | TC1 | TC2 | TC3 |
|---|---|---|---|
| (-) 10 | 2410 | 1538 | 1103 |
| 00 | 2398 | 1712 | 1040 |
| 05 | 2387 | 1795 | 1035 |
| 15 | 2492 | 2078 | 1025 |
| 22 | 2512 | 2205 | 1120 |
| 28 | 2440 | 2225 | 1116 |

### Stack Solids:

| Source | Weight grams | % of Wt. of Fuel Burned | Unburned Carbon-% |
|---|---|---|---|
| Quenching unit | 13.6 | 0.363 | 49.81 |
| Exhaust pipe | 20.4 | 0.545 | 88.04 |
| Separator | 25.9 | 0.691 | 84.39 |
| | 59.9 | 1.599 | 77.78 |

Gas Analysis:

$CO_2$ - 13.5%

$O_2$ - 2.3

$H_2$ - .73

CO - 1.29

$CH_4$ - .77

$N_2$ - 81.41

100.00

## Run 3:

Fuel - Commercial Bunker "C".

Fuel temperature (150 SSU) - 205°F

Quantity burned - 8.81 lb.

Time - 35 min.

Rate - 0.252 lb/min.

Average Air Temperature - 100°F

Air Rate - 52.0 cu.ft./min. (50 MM $H_2O$)

Excess Air (Meter) - 6.25%

Excess Air (Gas Analysis) - 21.6%

H/C ratio " " - 1.63

Temperatures (°F):

| Time (Min.) | TC1 | TC2 | TC3 |
|---|---|---|---|
| (-) 07 | 2465 | 1770 | 998 |
| (-) 01 | 2505 | 1770 | 990 |
| 07 | 2505 | 2005 | 1040 |
| 15 | 2505+ | 2200 | 1075 |
| 18 | 2505+ | 2270 | 1050 |
| 25 | 2505+ | 2340 | 1083 |
| 30 | 2505+ | 2340 | 1083 |

Stack Solids:

| Source | Weight grams | % of Wt. of Fuel Burned | Unburned Carbon-% |
|---|---|---|---|
| Quenching unit | 10.9 | 0.273 | 44.12 |
| Exhaust pipe | 21.6 | 0.541 | 87.20 |
| Separator | 26.4 | 0.661 | 89.09 |
| | 58.9 | 1.475 | 80.08 |

Gas Analysis:

$CO_2$ - 11.84%

$O_2$ - 5.20%

CO - 0.20%

$CH_4$ - 0.27%

$N_2$ - 82.49%

100.00

Run 4:

Fuel - Navy Special

Fuel Temperature (150 SSU) - 137°F

Quantity burned - 8.40 lb.

Time - 42 min.

Rate - 0.200 lbs./min.

Average Air Temperature - 100°F

Air Rate - 52.0 cu.ft./min. (50 MM $H_2O$)

Excess Air (Meter) - 34.2%

Excess Air (Gas Analysis) - 28.7%

H/C ratio - 1.76

Temperatures:

| Time (Min.) | TC1 | TC2 | TC3 |
|---|---|---|---|
| (-) 02 | 2405 | 1625 | 1040 |
| 04 | 2185 | 1485 | 970 |
| 09 | 2180 | 1600 | 998 |
| 19 | 2210 | 1780 | 1010 |
| 27 | 2230 | 1860 | 1020 |
| 34 | 2230 | 1920 | 1005 |

Solids:

| Source | Weight grams | % of Wt. of Fuel Burned | Unburned Carbon-% |
|---|---|---|---|
| Quenching Unit | 5.8 | 0.152 | 39.00 |
| Exhaust pipe | 2.4 | 0.063 | 58.94 |
| Separator | 4.6 | 0.121 | 78.67 |
|  | 12.8 | 0.336 | 56.95 |

Gas Analysis:

$CO_2$ - 12.35%

$O_2$ - 4.70%

$N_2$ - 82.95%

100.00%

Run 5:

Fuel - Navy Special

Fuel Temperature (150 SSU) - 137°F

Quantity burned - 8.45 lb.

Time - 39 min.

Rate - 0.216 lb./min.

Average Air Temperature - 100°F

Air Rate - 58.8 cu.ft./min (64 mm $H_2O$)

Excess Air (Meter) 40.0%

No gas analysis

Temperatures (°F:)

| Time (Min.) | TC1 | TC2 | TC3 |
|---|---|---|---|
| 00 | 2500+ | 2005 | 1040 |
| 10 | 2250 | 1920 | 1015 |
| 20 | 2111 | 1869 | 973 |
| 30 | 2200 | 2063 | 1065 |
| 35 | 2280 | 2092 | 1054 |

Solids:

| Source | Wt.grams | Wt.% fuel burned |
|---|---|---|
| Quenching unit | 6.6 | 0.172 |
| Exhaust pipe | 1.0 | 0.026 |
| Separator | 7.3 | 0.191 |
|  | 14.9 | 0.389 |

## SAMPLE CALCULATIONS

**Combustion Calculations:**

Furnace to burn Bunker "C" fuel oil, assuming an analysis as follows:

$H/C = 1.4$
API Gravity = 10.7
Specific Gravity = .995
Assumed fuel rate = 2 gal./hr.
Assume 13.5% $CO_2$ in products.

$$\begin{array}{lll} & \text{Complete Comb.} & \frac{x}{1.35}\ \text{excess air} \\ CH_{1.4} + 1.35\,O_2 \longrightarrow & 1.0\ CO_2 & 1.0\ CO_2 \\ & 0.7\ H_2O & 0.7\ H_2O \\ & \frac{79}{21} \times 1.35\ N_2 & \frac{79}{21}(1.35 + x)\ N_2 \end{array}$$

$$\frac{1.0}{1.0 + x + \frac{79}{21}(1.35 + x)} = .135$$

$$x = .277$$

$$\%\ \text{excess air} = \frac{.277}{1.35} = .205 = 20.5\%$$

$$\text{Mols. air/mol. fuel} = \frac{100}{21} \times (1.35 + .277) = 7.75$$

$$\text{lb. air/lb. fuel} = 7.75 \times \frac{29}{13.4} = 16.76$$

$$\text{Fuel rate} = \frac{2}{7.48} \times 62.4 \times .995 = 16.61\ \text{lb./hr.}$$

$$= 1.24\ \text{mol./hr.}$$

$$\text{Air rate} = 16.61 \times 16.76 = 278\ \text{lb./hr.}$$

High heat value of fuel = 17,780 + 54 (API Gravity
= 17,780 + 54 (10.7)
= 18,360 Btu/lb.

$\Delta H_c = 18,360 \times 16.61 = 305,000$ Btu/hr. (water as liq.)
$\Delta H_{fg}(H_2O) = .7 \times 1.24 \times 18 \times 1060 = 16,560$ Btu/hr.
$\Delta H_c = 305,000 - 16,560 = 288,400$ Btu/hr. (water as vapor)

## Furnace Dimensions:

Design requirements:

1. Cross-section to be square 5.5 inches on side.
2. Firing rate = 170,000 Btu/hr. - cu. ft.
3. Top section to be tapered from 5.5 inch square to 3.0 inch square cross-section.
4. Height of tapered section = 12.5 inches.

$$\text{Furnace volume} = \frac{288,400}{170,000} = 1.698 \text{ cu. ft.}$$

$$\text{Volume top section} = \left(\frac{3.0 + 5.5}{2}\right)^2 \times \frac{12.5}{1728} = .130 \text{ cu.ft.}$$

$$\text{Volume main section} = 1.698 - .130 = 1.568 \text{ cu. ft.}$$

$$\text{Length main section} = \frac{1.568}{(5.5)^2} \times 144 = 7.5 \text{ ft.}$$

Total length = 7'6" + 1'0½" = 8' 6½"

## Estimation of Furnace Temperatures:

### 1. Theoretical flame temperature.

Assuming theoretical flame temperature = 3300 °F

| | N | $MC_p$ ave. | N $MC_p$ ave. |
|---|---|---|---|
| $CO_2$ | 1,24 | 12.92 | 16.02 |
| $H_2O$ | .868 | 10.33 | 8.97 |
| $O_2$ | .346 | 8.34 | 2.89 |
| $N_2$ | 7.60 | 7.92 | 60.2 |
| | | | 88.08 |

$$T_{Fl} = \frac{288400}{88.08} + 60 = 3335 \,^{\circ}F$$

2. Losses and furnace exit temperature.

Overall heat transfer coefficient for 4.5" brick and .125" steel casing.

$h_{ci} = 2.0$

$k_{brick} = 0.113$

$k_{steel} = 25.9$

$h_o = 0.27 \ \Delta T^{.25}$ (Eq. 16, p. 240, Ref. (11) )

$= 0.27 \ (100)^{\frac{1}{4}}$

$= 0.854$

$$U = \frac{1}{\frac{1}{2.0} + \frac{.375 \times 5.5}{.113 \times 10} + \frac{.0104 \times 5.5}{25.9 \times 10.0} + \frac{1 \times 5.5}{.854 \times 14.5}}$$

$= .361$ Btu/sq.ft.- °F.

The external losses are to be considered equal to the convection to the refractory.

$$(1) \quad q_F = \sigma \ (T_F^4 - T_C^4) \ A_C \ \frac{1}{\frac{1}{\epsilon_C} + \frac{A_C}{A_C + A_R} \left(\frac{1}{\epsilon_F} - 1\right)} + U_R A_R (T_F - T_O)$$

$$(2) \quad q_F = H_C + H_A - w_G \ (Cp)_m \ (T_{F_2} - T_O)$$

$$T_F = \frac{T_{F1} + T_{F2}}{2}$$

$$A_C = \overline{5.5}^2 \times \frac{1}{144} = 0.21 \text{ sq. ft.}$$

$$A_R = 5.5 \times \frac{1}{12} \times 7.5 \times 4 + 3.03 \times \frac{1}{12} \times 4 \times \frac{12.5}{12}$$

$= 14.80$ sq. ft.

From Ref. (11), p. 69 $\quad L = 1.06$

Assume $T_S = 120°F$ $\quad T_C = 3000°F$

$\epsilon_C = 0.8$

$$\epsilon_g = \epsilon_{CO_2, T_c, P_cL} + \epsilon_{H_2O, T_c, P_wL} C_1 - \Delta\epsilon_{T_c}$$

$P_C = \frac{1}{8.1} = .1234$ $\quad P_W = \frac{.7}{8.1} = .0865$

$P_CL = .131$ $\quad P_WL = .0917$

Assume $T_F = 3035$

$$\epsilon_{G, CO_2, T_G P_cL} = .033$$

$$\epsilon_{G H_2O, T_G P_wL} = .027$$

$$\epsilon_G = .083 + .0290 = .0620$$

$\propto$ term negligible

$$\epsilon_F = \frac{.0620}{1-(\frac{5.8}{34.6})^4} = .0621$$

(1) $q_F = 0.173 (\overline{34.95}^4 - \overline{5.8}^4) \times 0.21 \times .685 + .361 \times 14.8(3035 - 120)$

$= 36800 + 15600$

$= 52400$ Btu/hr.

(2) $q_F = 288400 - 88.1 \Delta T$

$$\Delta T = \frac{288400 - 52400}{88.1} = \frac{236000}{88.1} = 2680 °F$$

$$T_{F_2} = 2680 + 60 = 2740$$

$$T_F = \frac{2740 + 3335}{2} = 3037 °F$$

## Heat Transfer to Quenching Unit

| | N | $MC_p$ ave. (1500°) | N $MC_p$ ave. |
|---|---|---|---|
| $CO_2$ | 1.24 | 11.54 | 14.31 |
| $O_2$ | .868 | 7.80 | 2.68 |
| $N_2$ | .346 | 7.37 | 56.00 |
| $H_2O$ | 7.60 | 8.97 | 7.79 |
| | | | 80.78 |

$$q \text{ (to quenching unit)} = \Delta H_C - q_F - N\,MC_p \text{ ave.} (1500-60)$$

$$= 288{,}400 - 52{,}400 - 80.78\ (1440)$$

$$= 119{,}800 \text{ Btu/hr.}$$

Assuming the water temperature rise = 20°F

$$w = \frac{q}{C\,\Delta T} = \frac{119{,}800}{20} = 5990 \text{ lb./hr.}$$

$$= 718 \text{ gal./hr.}$$

$$= 11.97 \text{ gal./min.}$$

## Heat Transfer Surface of Quenching Unit.

No. tubes = n

Tube thickness (outside) = 3/16"

Tube spacing = 1/8"

Tube height = 2.88"

$$\frac{3n}{16} + \frac{n+1}{8} = 6\ 1/16$$

$$5n + 2 = 97$$

$$n = \frac{95}{5} = 19 \text{ tubes}$$

Area tubes $= (2 \times 2.88 + 3/16\pi)5.5 \times 19 \times \frac{1}{144}$

$= 4.61$ sq. ft.

Log mean temperature difference:

Gases to be cooled from 2740°F to 1500°F.
Water assumed to rise from 60°F to 80°F.

$$\Delta T_m = \frac{(2740-60) - (1500-80)}{\ln \frac{2680}{1420}}$$

$$\Delta T_m = 1982°F$$

Heat transfer coefficient (Fig. 111, p. 221, Ref.(11))

$$\mu_f = 2.42 \times .0385$$

$$G = \frac{278 \times 144}{5.5 \times 20 \times 1/8} = 2910 \text{ lbs./hr.- sq. ft.}$$

$$D_e = \frac{\text{perimeter}}{\pi} = \frac{2.88 \times 2 + 3/16\pi}{\pi} \times \frac{1}{12} = .1687 \text{ ft.}$$

$$\frac{D_e G}{\mu} = \frac{2910 \times .1687}{2.42 \times .0385} = 5.27 \times 10^3 \qquad \frac{h D_e}{k} = 39$$

$$h = \frac{.0339 \times 39}{.1687} = 7.84 \text{ Btu/hr.- sq.ft.- °F.}$$

Heat transfer to quenching unit:

$$q = hA\,\Delta T_m$$

$$= 7.84 \times 4.61 \times 1982$$

$$= 71{,}700 \text{ Btu/hr.}$$

## SAMPLE CALCULATIONS

Percent excess air by meter:

The quantity of oil burned and the time for the run were observed. The following calculations were made for Run #1:

Quantity - 7.65 lb.

Time - 31 min.

Rate = 7.65/31 = 0.247 lb./min

The theoretical air is based on the percent carbon and hydrogen for the Navy Special Fuel Oil given in the properties of the oil.

$$a = \left[\frac{C}{12} + \frac{H}{4} - \frac{O}{32}\right] \frac{1}{.21}$$

where a = Theoretical air

C, H, and O = Fraction by weight

$$a = \left[\frac{0.857}{12} + \frac{.114}{4} - \frac{0}{32}\right] \frac{1}{.21}$$

$$= 0.475 \text{ mols/lb fuel}$$

$$Q_a \text{ (at } 100^\circ F) = 0.475 \times 359 \times \frac{560}{492} = 194.5 \text{ cu.ft./lb fuel}$$

$$= 194.5 \times 0.247 = 48.0 \text{ cu.ft./min}$$

The air supplied is obtained from the flow equations for sharp-edged orifices given in the A.S.M.E. "Fluid Meters." (12). The equation used was:

$$Q_a = 0.0997\ KY_1\ D_2^2 \sqrt{\frac{h_w}{P_1}}$$

$Q_a$ = Volumetric flow rate, cu.ft./sec

$K$ = Discharge coefficient

$= C / \sqrt{1 - \beta^4}$

$\beta$ = Diameter ratio

$C$ = Velocity coefficient

$Y_1$ = Expansion factor

$D_2$ = Orifice diameter

$h_w$ = Differential pressure, inches of water

$P_1$ = Density of air at inlet pressure and temperature.

The curves for the expansion factor and tables of values of K versus Reynold's Number are reproduced in Figure XII for the diameter ratio and size of air piping used. For Run 1 assume $R_d$ = 63,000 and the corresponding value of K is,

$$K = 0.626$$

The effect of compressibility is negligible for the differential pressure used (about 2")

$$P_1(100^\circ F) = \frac{28.97 \times 492}{359 \times 560} = .071$$

$$h_w = 50 \text{ MM of } H_2O = 1.97" \; H_2O$$

$$Q_a = .0997 \times .626 \times 2.64 \sqrt{\frac{1.97}{0.071}} \times 60$$

$$= 52.0 \text{ cu.ft./min}$$

Checking the assumed value of $R_d$:

$$\text{Orifice Area} = \frac{\pi(1.44)}{4} \times \frac{1}{144} = 0.00785 \text{ ft}^2$$

$$\text{Velocity} = \frac{52.0}{0.00785} \times \frac{1}{60} = 110.3 \text{ ft/sec.}$$

$$R_d = \frac{PVD}{\mu} = \frac{0.071 \times 110.3 \times 0.1}{0.0185 \times 6.72 \times 10^{-4}} = 63,000$$

If Reynold's number differs very much from assumed value a new calculation must be made for the air rate. Variation of the discharge coefficient with Reynold's number however, is small.

Percent excess air = $e$

$$e = \frac{52.0 - 48.0}{48.0} = 8.33\%$$

The same procedure is used for the commercial Bunker "C" except the percentages by weight of carbon and hydrogen are not known. The theoretical air was assumed to be the same as for the Navy Special.

Percent excess air and H/C ratio from Gas analysis:

Run 1

$CO_2$ - 13.3

$H_2$ - 0.32

$O_2$ - 2.14

CO - 1.07

$N_2$ - 83.17

Equivalent $O_2 = 83.17 \times \frac{21}{79} = 22.10$ mols

Mols of $O_2 = 13.3 + 2.14 + 0.54 = 15.98$

Net $O_2 = 6.12$

Atoms $H = 6.12 \times 4 + 2 \times .32$

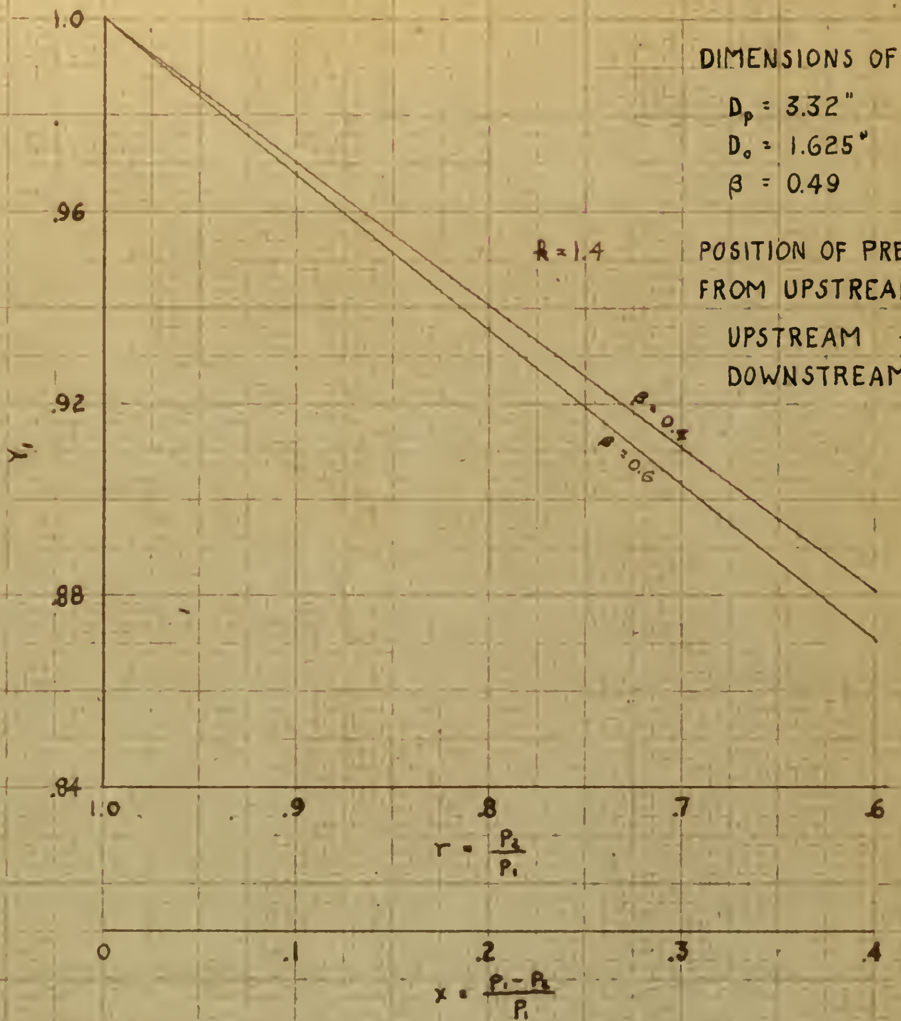
H/C ratio $= 25.12/14.37 = 1.76$

$$\text{Excess } O_2 = \frac{2.14 - \frac{1.07 + .32}{2}}{\frac{21}{79} \times 83.17 - \left(2.14 - \frac{1.07 + .32}{2}\right)}$$

$$= 7.0\%$$

FIG. XIII

EXPANSION FACTOR FOR FLANGE, RADIUS, & VENA CONTRACTA TAPS



DIMENSIONS OF METERING ORIFICE

$D_p = 3.32"$

$D_o = 1.625"$

$\beta = 0.49$

POSITION OF PRESSURE TAPS FROM UPSTREAM FACE:

UPSTREAM — 3.34"

DOWNSTREAM - 1.625"

$$Y_1 = 1 - (0.41 + 0.35\beta^4)\frac{x}{k}$$

VALUES OF "K" FOR VARIOUS VALUES OF $R_d$

$R_d \times 10^{-3}$

| β | 25 | 35 | 50 | 75 | 100 | 150 | 250 | 500 | 1000 |
|---|---|---|---|---|---|---|---|---|---|
| 0.45 | .623 | .6213 | .6197 | .6183 | .6174 | .6164 | .6154 | .6144 | .6137 |
| 0.50 | .6327 | .6309 | .6292 | .6277 | .6268 | .6257 | .6246 | .6236 | .6228 |
| 0.49 | .6308 | .6290 | .6273 | .6258 | .6249 | .6238 | .6228 | .6218 | .6210 |

$\beta = \frac{\text{ORIFICE DIAM.}}{\text{PIPE DIAM.}}$

$R_d$ = REYNOLDS NO. AT THROAT

$K = \frac{C}{\sqrt{1-\beta^4}}$

C = VELOCITY COEFF.

JAN 8, 1948

REPRODUCED FROM A.S.M.E. RESEARCH COM. ON FLUID METERS - SEE [12]

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